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Braking ground reaction force during 90deg sidestep cut and its relationship to leg muscle strength

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ABSTRACT

Previous studies on change of direction (COD) have reported that braking is an important factor for COD performance. However, previous studies have focused on the plant step and the penultimate step (PEN), thus little is known about deceleration before these steps. This study compared ground reaction forces (GRF) of two braking steps, the PEN and the step prior to PEN (PEN-1), the entry and exit velocity of the COD, and muscle function measures (leg press and leg curl one-repetition maximum, isometric and isokinetic strength, and drop jump performance) between faster and slower participants for a 90^{o} sidestep cut. This study also examined the associations between the time taken from 1 m before and 1 m after COD (1-1 m COD time), braking GRF during deceleration and muscle function. Twenty-two male recreational athletes from AFL (n = 2), soccer (n = 8), rugby (n = 2), basketball (n = 5), squash (n = 1) and tennis (n = 4), performed a total of six cuts with their dominant (DL) and non-dominant legs (NDL). The faster group (n =10; DL: 0.19 ± 0.02 s, NDL: 0.22 ± 0.02 s) and the slower group (n = 10; DL: 0.24 ± 0.02 s, NDL: 0.31 ± 0.04 s) as well as pooled (n = 20) DL and NDL (DL: 0.21 ± 0.03 s, NDL: 0.26 ± 0.04 s) were used for analyses. Dependent variables between the groups were compared using independent t-tests with sequential Bonferroni corrections to control for type I error. Pearson's correlation was used to examine the relationship between the 1-1 m COD time and dependent variables. Faster DL COD participants showed significantly greater change in braking impulse from PEN-1 to PEN (-0.50 ± 0.31 vs -0.20 ± 0.15 m·s^{-1}, p = 0.027) whereas faster NDL COD participants showed greater isometric knee flexor torque (1.94 ± 0.25 vs 1.63 ± 0.26 Nm·kg^{-1}, p = 0.005), isometric extensor torque (3.37 ± 0.42 vs 3.17 ± 0.71 Nm·kg^{-1}, p = 0.017) and concentric isokinetic (90^{o}·s^{-1}) knee extensor torque (3.02 ± 0.47 vs 2.47 ± 0.39 Nm·kg^{-1}, p = 0.03). Pooled DL and NDL comparison revealed significantly higher plant step braking impulse (0.61 ± 0.23 vs 0.47 ± 0.23 m·s^{-1}, p = 0.043) and

lower propulsive impulse (2.42 ± 0.47 vs 2.77 ± 0.47 $m \cdot s^{-1}$, $p = 0.008$) during DL COD. Faster NDL COD was associated with greater NDL eccentric knee flexor at $90^{o} \cdot s^{-1}$ ($r = 0.648$, $p = 0.003$), 60 cm drop jump ($r = 0.556$, $p = 0.010$), greater NDL isometric knee flexor torque ($r = 0.473$, $p = 0.024$) and greater NDL eccentric knee extensor at $90^{o}s^{-1}$ ($r = 0.470$, $p = 0.041$). These results indicate that mechanical factors influencing DL and NDL COD performance were different. In addition, deceleration steps ranged between three to five steps with braking between PEN-1 and PEN resulting in faster DL COD performance. Further studies are is required to examine the deceleration starting at PEN-1 and should consider multifactorial analyses to capture multiple strategies potentially implemented.

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

i. incorporate without acknowledgment any material previously submitted for a degree or diploma in any institution of higher education
ii. contain any material previously published or written by another person except where due reference is made in the text of this thesis
iii. contain any defamatory material

Signed: Walter YU

Date: 14 December 2018

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Chapter 1. INTRODUCTION

1.1 Agility and Change of Direction

Agility is an athletic ability that is required for field and court sports (Brughelli et al., 2008). Sheppard et al. (2006a) defined agility as a "rapid whole-body movement with change of velocity or direction in response to a stimulus," and stated that the speed of which a change of direction (COD) was performed and perceptual factors during the agility task were the two main components contributing to agility. Assessment of COD performance is typically carried out by using pre-planned tasks as seen in the 505, T-test, Illinois, Pro-agility and L-run tests (Sheppard et al., 2006a; Stewart et al., 2014). Tests that assess the perceptual component of agility have been referred to as reactive agility tests (Sheppard et al., 2006b; Spiteri et al., 2015b), because they introduce cognitive demands by using video, light or human stimulus to dictate the direction of the COD task (Lockie et al., 2013b; Young et al., 2015b; Young et al., 2014). In their review paper, Young et al. (2015a) concluded that perceptual factors of agility differentiated elite level athletes from sub-elite athletes, but the overall COD speed did not, differentiate the level of athletes and no significant differences in COD speed between groups were observed. Although perceptual factors differentiated the two levels of athletes, agility tasks still require the coordination of multiple limbs (Paul et al., 2016). As eloquently put forth by Araujo et al. (2006), "without decisions being realised through action, cognition would remain forever locked in a black box." Therefore, it is still necessary to investigate and understand the physical factors that contribute to COD ability. In particular the mechanisms underpinning performance of a COD task, exclusive of perceptual-cognitive measures, to better understand if the physical capacity is present prior to increasing complexity of the task to include a perceptual-cognitive component.

1.2 Assessment of Change of Direction

1.2.1 Common measures of COD ability and the need to "isolate" performance

To assess the physical ability to change direction, performance is often measured by the total time to complete a COD task (Sayers, 2015; Stewart et al., 2014). Other variables such as the GRF, joint kinetics and kinematics during the COD task are also recorded to understand the mechanical factors that contribute to the performance of the COD task, particularly the final step whereby the actual COD movement is performed (Besier et al., 2001a; Havens et al., 2015; Inaba et al., 2013; Spiteri et al., 2015b). However, there is no "gold standard" COD test, as COD test selection depends on the sport or purpose of the research (Nimphius et al., 2017). For example, the T-test COD test is recommended for basketball, since the test contains movements frequently used in basketball such as side-shuffle, back pedalling and forward runs (Spiteri et al., 2015a), whereas a 505 COD test is often utilised for cricket players as they are required to make only 180° turns during the game (Lockie et al., 2013a; Nimphius et al., 2016).

Despite the lack of an universally agreed upon "gold standard" COD test, there are five COD tests that have been identified as most commonly used in performance assessment as well as used in performance based assessments and research, the Illinois agility test, L-run, Pro agility, T-test and 505 test (Stewart et al., 2014). Stewart et al. (2014) investigated the reliability and correlation of these five COD tests, using the total time for each test, and found low variation (CV% 1.95 – 2.40%) and correlation (r = 0.84 - 0.89, $p \leq 0.01$) between all five COD tests, despite their varying distance, number of turns and turning intensity. The significantly high correlation may suggest that these COD tests may not be a specific measure of COD ability, but rather a test of general athletic ability (Stewart et al., 2014). Further, a portion of the correlations may be explained by the large amount of linear sprinting in each test, since as high as 69% of the total time in 505 COD test involves linear sprinting (Nimphius et al., 2013). As such, the total time for COD performance may not differentiate the physical demands required to effectively perform a COD such as rapid acceleration and deceleration before the COD step, control and transfer of momentum to the new direction and acceleration after the COD step (Nimphius et al., 2017; Nimphius et al., 2013; Sayers, 2015). Recent studies have attempted to determine better ways of assessing COD by removing linear sprint ability from the total time assessment to focus on the COD movement (Lockie et al., 2017; Nimphius et al., 2016; Sayers, 2015).

Total time during COD tests does not represent COD performance due to the large amount of linear sprint involved. This is supported by COD total times being highly correlated ($r > 0.7$) with linear sprint times of 10-m, 20-m and 40-m (Lockie et al., 2013b; Sayers, 2015). Therefore, an athlete may have poor COD ability but be able to perform a COD test in by having superior linear speed to make up for poor COD ability (Nimphius et al., 2017). Furthermore, the amount of linear sprinting involved during a COD tests may also increase the duration of the test and therefore assess anaerobic capacity instead of COD (Brughelli et al., 2008). As such, it is recommended that COD test attempts isolate the time surrounding the COD movement (push-off) to assess COD performance (Nimphius et al., 2017; Sayers, 2015).

In a study conducted by Sayers (2015), isolating linear sprint ability from COD task has been performed by assessing the time of short distances of 0.3-m, 0.5-m and 1-m before and after the COD step, measured by a 3D motion capture system The results of this study showed that the smaller measurement windows of 0.3-m and 0.5-m had non-significant moderate correlations to linear sprint ability while a 1-m had moderate to large correlation to linear sprint of 5-m (0.3-m: $r = 0.50$; 0.5-m: $r = 0.53$; 1-m: $r = 0.66$), 10-m (0.3-m: $r = 0.52$; 0.5-m: $r = 0.56$; 1-m: $r = 0.65$) and 20 m timings (0.3-m: $r = 0.58$; 0.5-m: $r = 0.64$; 1-m: $r = 0.72$) but large significant correlation to 505 COD task (0.3-m: $r = 0.74$; 0.5-m: $r = 0.77$; 1-m: $r = 0.87$). These results suggest that the 0.5-m method is effective in reducing the impact of linear sprint from COD task. The test-retest reliability of 1-m distance was high (ICC = 0.82, CV% = 2.4%, TEM = 0.024), but the reliability decreased when the distance was 0.3-m and 0.5-m (ICC = 0.65 -

0.72, CV% = 3.5 -4.5%, TEM = 0.024). A 1 m distance seems to be an effective compromise in reducing the impact of linear sprint performance from the COD task while maintaining reliability (Sayers, 2015). Using a 1-m window (1-m prior to the plant step and 1-m after the plant step) may also allow enough distance to use timing gates to measure COD performance directly without false triggering of the timing gates by body lean or arm swings (Nimphius et al., 2017)

1.2.2 Techniques used to change direction

Another significant aspect of a COD test is an athlete's technique, since techniques used during a COD has an impact on the biomechanics observed during the COD task (Besier et al., 2001b; Nimphius, 2014; Suzuki et al., 2014). Three techniques have been identified when performing a COD task, the by-pass manoeuver, sidestep cut and crossover cut (Andrews et al., 1977; Besier et al., 2001b; Rouissi et al., 2015). The by-pass manoeuver is described as "multiple short steps to avoid reduction in running speed by performing longer distance and wide angle of COD" (Rouissi et al., 2016; Rouissi et al., 2015). The by-pass manoeuver technique is used to perform a COD with wider radius and is observed during the L-run COD test (Nimphius, 2014) or sometimes when technical instructions for a COD task is not specified and the angle of COD is small (Condello et al., 2016). However, the large turning radius that is required for this technique may also limit its application in real match situations as the opponent will be able to anticipate the intention and direction much earlier and react according. During real match situations a sidestep cut or crossover cut is a more effective COD technique, as it can be performed quickly without giving away any intention to the opponent (Wheeler et al., 2011).

The cutting movement is described as a movement into a new direction in one step (Spiteri et al., 2013; Wheeler et al., 2010b). The movement of cutting is important in athletic performance as an evasion tactic in team sports such as rugby (Wheeler et al., 2010b), and has been observed when evading a defensive player (Bloomfield et al., 2007; McLean et al., 2004). Within the cutting movement, there are two techniques, the sidestep cut and crossover cut (Andrews et al., 1977; Suzuki et al., 2014). During the sidestep cut technique, the contralateral leg is used to propel the body and the ipsilateral leg is used for the first step in the new direction. Whereas during a crossover cut technique, the contralateral leg crosses in front of the body for the first step in the new direction (Suzuki et al., 2014). The sidestep cut technique may be a preferred and more effective technique as studies have shown the frequency and importance of the sidestep cut technique in rugby to create scoring opportunities and evade opponents (Wheeler et al., 2010a; Wheeler et al., 2010b). Wheeler et al. (2010a) reported that sidestep cut was used 37% during a rugby game compared to only 5% of evasions by crossover cut. Furthermore, the sidestep cut was a more effective technique as 84% of successful evasive sidestep cut performed resulted in a score.

Sidestep and crossover step techniques of COD vary significantly in their kinetics and kinematics. Suzuki et al. (2014) reported that a higher decrease in entry velocity for sidestep (-0.63 ± 0.23 m·s-^{1}) than crossover cut (-0.31 ± 0.23 m·s^{-1}), while exit velocity was similar between sidestep (0.43 ± 0.12 m·s^{-1}) and crossover step (0.41 ± 0.12 m·s^{-1}). Similarly, Besier et al. (2001b) compared the sidestep cut and crossover step at 30° and found that the COD was achievable using both techniques with no little reduction in speed but subjects were unable to reach 60^{o} COD even with significant reduction in running speed using the sidestep cut. Besier et al. (2001b) did not examine a 60^{o} crossover cut, however a crossover cut may less preferred and harder to perform than a sidestep cut for higher angle COD (Green et al., 2011) . Besier et al. (2001b) and Suzuki et al. (2014) compared the kinetics and kinematics between the sidestep cut and crossover cut, and showed that when COD angles were shallow, little reduction in speed was needed to complete the COD task. Therefore, higher angle (> 60°) COD should be examined to ensure COD tests would not be performed with a slight curving strategy with less braking (Condello et al., 2016; Vanrenterghem et al., 2012).

1.2.3 Kinetics and kinematics of braking during COD

Although a majority of research has focused on the plant step during a COD (Besier et al., 2001b; Condello et al., 2016; Spiteri et al., 2013), there has been acknowledgement of the importance of braking kinetics on whole-body kinematics or COM velocity as a measure of performance (Dos'Santos et al., 2018; Havens et al., 2015; Jones et al., 2016a). Havens et al. (2015) showed that velocity decreased from the penultimate (second to the last) step (4.15 ± 0.32 m·s^{-1}) to the final step (3.84 ± 0.35 m·s^{-1}), while the velocity increased from the penultimate step (5.83 ± 0.45 m·s^{-1}) to final (5.95 ± 0.48 m·s^{-1}) step for a 45° cut. Similarly, Dos'Santos et al. (2018) reported in a recent review that substantial braking force is required for COD angles between 60^{o} to 180^{o}, whereas COD angles less than 45^{o} requires minimal braking and velocity should be maintained. Therefore, an experimental design using the 90° sidestep cut seems to be suitable for studying braking force during a COD, as it is within the range of COD angles whereby forward momentum during running must be reduced by braking to successfully make a 90° sidestep cut (Dos'Santos et al., 2018; Havens et al., 2015). Jones et al. (2016a) investigated braking during a sidestep 90° cut and reported that peak braking force relative to body mass at the penultimate step was 13% greater than at the final step. Similarly the braking impulse relative to body mass during the penultimate step was also 17% greater than that during the final step. They concluded that the penultimate step was a crucial and demanding step for COD, as peak braking force and total impulse were higher for the penultimate step than the final step (Jones et al., 2016a). Similarly, Nedergaard et al (2014), observed three braking steps (plant, penultimate and one step prior to the penultimate) during a 135^{o} COD deceleration and reported that the penultimate and one step prior to penultimate had significantly ($p \leq 0.05$) greater trunk deceleration than the plant step. Theoretically, if there is less forward momentum during the final step, more force can be applied in the lateral direction, therefore attaining a higher exit velocity in the new direction (Spiteri et al., 2013). Therefore, it is crucial to further understand the deceleration mechanics from the onset of deceleration, as deceleration during a COD occurs over a series of steps rather than at the penultimate step.

Proficient braking may also improve higher angle COD performance as it reduces the time to reach the manageable load for transferring the centre of mass to a new direction thus allowing high velocity linear sprints for a longer distance (Dos'Santos et al., 2016; Spiteri et al., 2013; Spiteri et al., 2015a). Previous studies have examined the mechanical braking factors such as ground contact time and velocity before and after the COD in faster and slower performers as well as braking strategies expressed as the ratio of braking force between the penultimate and plant step (Dos'Santos et al., 2016; Spiteri et al., 2013). Spiteri et al. (2013) reported that participants who performed the COD task faster, applied greater braking force and impulse during the COD plant step and subsequently had significantly faster exit velocities when compared to the slower participants. Braking force in the penultimate step was also higher in faster athletes compared to slower athletes. This early braking reduces forward momentum during the final step, more force can be applied in the lateral direction, therefore attaining a higher exit velocity in the new direction through higher propulsive impulse (Spiteri et al., 2013). Greater braking ratio (higher braking at the penultimate step relative to the plant step) has also been observed to not only be correlated to COD performance during a 505 test ($r = 0.429$), but also observed to be one of the significant ($p < 0.01$) differentiating qualities between faster and slower performers (Dos'Santos et al., 2016). These indicate the importance of early braking in improving COD performance and physical function associated with braking.

1.3 Influence of muscle function and COD braking performance

It is well documented that eccentric muscle actions of the lower limb musculature contribute to the deceleration of the body during COD tasks (Brughelli et al., 2008; Sheppard et al., 2006a; Suchomel et al., 2016). Therefore, lower extremity eccentric strength may provide the capacity to effectively decelerate the centre of mass as well as to control the posture during the braking phase of a COD task (Brughelli et al., 2008; Nimphius, 2014; Suchomel et al., 2016). Therefore, it is important to assess the contribution of eccentric strength to braking prior to or during a COD task. It is possible that athletes who are better at COD have greater eccentric strength relative to body mass in the lower limb musculature when compared with those who exhibit poor COD ability. Some studies have investigated eccentric strength in relation to COD (Chaouachi et al., 2012; Jones et al., 2009; Lockie et al., 2014b; Spiteri et al., 2015a; Spiteri et al., 2014). For example, Jones et al. (2009) reported a significant relationship between COD performance (505 test) and maximal eccentric strength of the knee flexors (r = -0.592) and extensors (r = -0.506), assessed by an isokinetic dynamometer at the angular velocity of $60^{o} \cdot s^{-1}$. They suggested that there was a higher requirement of eccentric knee flexor strength together with other hip extensors to maintain trunk position during a lowered stance during COD. Single-joint movement may not adequately explain COD movements which is a multi-joint movement (Spiteri et al., 2015a; Spiteri et al., 2015b; Spiteri et al., 2014). Therefore, the knee flexor and extensor eccentric strength assessed by the isokinetic dynamometer may not represent the eccentric capability required during a COD task (Jones et al., 2009; Spiteri et al., 2015b).

An athlete's lower body is required to move through a large range of motion with multiple joints during a COD (Nimphius, 2014). Therefore, strength assessments such as an eccentric squat 1RM, leg press 1RM and/or drop jump task may be better when assessing relationships between COD and eccentric capability as they will be specific to the multi-joint strength requirements during COD (Brughelli et al., 2008; Suchomel et al., 2016). Additionally, Jones et al. (2016) showed that plant step knee flexion of 60^{o} during a COD cut, as this phase of the COD is isometric (Brughelli et al., 2008; Sheppard et al., 2006a; Spiteri et al., 2014), it is likely that faster athletes have greater isometric strength at 60^{o} knee flexion than slower athletes. Furthermore, the knee moves at a high angular velocity during deceleration (Jones et al., 2016a; Nedergaard et al., 2014) and testing isokinetic strength at higher velocities, such as 90^{o} s^{-1} and 180^{o} s^{-1}, may provide further insight of the knee extensor and flexor strength requirements during deceleration. Drop jump task assesses an athlete's ability to rapidly change from eccentric to concentric muscle action (Markwick et al., 2015), which is an important mechanism during COD plant step for the storage and utilisation of elastic energy during the braking and propulsive phase of the plant step (Spiteri et al., 2013). Assessing muscle function with a larger range of test will further the understanding of muscular contribution during COD movement.

Cross-sectional studies of faster and slower COD performance can reveal general technical and strength differences and provide knowledge to practitioners and researchers regarding the characteristics of those with better COD performance. Faster athletes during a T-test were found to have significantly ($p < 0.05$) higher eccentric knee flexor strengths capacity, faster 505 COD test time and 5-m sprint time than slower athletes (Chaouachi et al., 2012). Similar results was found that athletes who performed faster 505 COD task, who were significantly stronger, isometrically and eccentrically than slower athletes (Spiteri et al., 2015a). Faster athletes may be able to decelerate faster during the penultimate step due to greater eccentric strength of the knee extensor and flexor as shown by Jones et al. (2017). They demonstrated that athletes with greater eccentric knee extensors and flexors strength decelerated significantly ($p < 0.05$) faster and from a higher approach velocity at the penultimate step than weaker athletes. The greater reduction in velocity prior to the COD plant step may partially explain faster COD times as less time will be spent for deceleration and more time on acceleration during the COD plant step. However, the influence of braking steps before the penultimate step has not been investigated.

1.4 Summary

It is necessary to further investigate the physical factors and mechanisms underpinning COD ability before increasing complexity of the task to include a perceptual-cognitive component. There is a need for a more specific measurement such as the 1-1m COD time to investigate COD performance rather than the total time measure of COD performance, but the reliability of this measure has not been examined. With regards to the kinetics and kinematics during COD, recent studies have focused on the importance of braking kinetics on whole body kinematics on top of the kinetics of the COD plant step, but only the penultimate step braking kinetics have been examined. It is likely that deceleration occurs over several steps rather than at the penultimate step, thus more steps during deceleration needs to be examined. It is possible that faster COD performance is associated with higher braking impulse at the penultimate step and with greater eccentric strength of the knee extensors and flexors. However, as COD is a multi-joint movement, assessing associations between COD and eccentric capability using leg press and drop jump task may be better than single joint assessment using an isokinetic dynamometer.

1.5 Purpose of the Thesis

The purpose of this thesis was to examine the braking kinetics of the steps occurring during deceleration, such as the plant and penultimate steps and prior steps, of a 90° sidestep cut by comparing between faster and slower COD performers based on 1-1m COD time, and to examine the association between muscle function, braking kinetics and COD performance.

1.6 Research Questions and Hypotheses

1) Is there a difference in GRF between participants with faster COD and slower COD (as defined by 1-1 m time) in a 90° cut?

Hypothesis: There would be difference in braking impulse during the PEN and PEN-1 steps, and higher propulsive impulse during the plant step for faster 1-1m COD performance.

2) Is there a difference in muscle function between faster and slower COD performance?

Hypothesis: There would be a difference between faster and slower COD performance in maximal eccentric strength and isokinetic eccentric strength at higher angular velocities.

3) Is there an association between braking GRF and COD performance (1-1 m COD time)?

Hypothesis: COD performance would be associated with higher braking impulse during the PEN and PEN-1 steps.

4) Is there an association between muscle function and COD performance?

Hypothesis: COD performance would be associated with maximal eccentric strength, isokinetic eccentric knee flexor strength and drop jump reactive strength index.

1.7 Limitations

Participants were recruited from various sporting background with varying degrees of proficiency in their chosen sport, ranging from club level to state league. Additionally, five participants were from racket sports and does not perform COD movements from a run up frequently. This may influence the amount of COD and training for COD they had received, which may influence the COD performance assessed in the study. The space constraint limited the COD task to 3 m linear sprint after the COD plant step, which might hinder some participants from sprinting maximally after the COD plant step. Due to time constraints a familiarisation session was combined with the first session of data collection. Footwear was not standardised in this study, but every participant was briefed to wear shoes with flat soles to have maximal traction to the floor.

1.8 Delimitations

The findings of this study should be delimited to males aged between 18 to 30 years old with no lower body musculoskeletal injuries. Further, the study results may be delimited further as it was conducted on an indoor surface and the resulting kinetics may not reflect actual COD performed on grass field or other indoor surfaces.

Chapter 2. METHODS

2.1 Experimental Design

This study used a between-subject design to examine the biomechanical factors (GRF and centre of mass velocity) of the last three steps during COD and lower body muscle functions (drop jump reactive strength index from three heights, unilateral leg press 1RM, unilateral leg curl 1RM and unilateral isokinetic strength) that might differentiate faster and slower COD performance (1-1 m COD time). Additionally, this study also examined the relationship between the biomechanical factors during the last three steps of COD and lower body muscle functions and COD performance. Participants were required to attend five sessions; session one consisted of the COD task familiarisation, COD task and GRF measurement; session two consist of COD task and GRF measurements; sessions three consisted familiarisation of all muscle function tests; session four consisted of 1RM unilateral leg press and 1RM unilateral leg curl assessments; session five consisted of drop jump reactive strength index (RSI), unilateral isometric and unilateral isokinetic strength assessments. All sessions were separated by at least 48 hours. Participants were advised not to perform any strenuous activities within 48 hours before the testing session.

2.2 Participants

Twenty-two young men were recruited from the Edith Cowan University sports teams, Sports Science students and local sports clubs. The inclusion criteria required participants to have at least two years of experience in playing a chosen sport and have undertaken a minimum of one training session a week and one competitive game a week during competition season or two training sessions a week during off season. All participants were also required to have been resistance training for at least one year. Participants were from AFL (n = 2), soccer (n = 8), rugby (n = 2), basketball (n = 5), squash (n = 1) and tennis (n = 4). Their mean age, body mass and height were 22.4 ± 3.4 years, 73.5 ± 6.7 kg, and 177.3 ± 5.6 cm, respectively. Body mass was measured with a digital scale (Tanita Corporation, Tokyo, Japan) and height was measured using a stadiometer (Ecomed Trading, Seven Hills, Australia). All participants were given an information letter (Appendix A), and subsequently read and signed an informed consent (Appendix B) before commencing the study. All participants completed a medical questionnaire in order to screen for contraindications to participate in the present study (Appendix C). They were informed that they were free to withdraw from the study at any time without prejudice. The medical questionnaire was used to screen for lower body musculoskeletal disorders and/or injuries in the past 6 months. The participants signed the final checklist form before starting the first session of the study (Appendix D). Ethical approval (Project Approval 17254YU) was obtained from the ECU Human Ethics Committee (Appendix F).

2.3 Procedures

2.3.1 COD task and ground reaction force measurement

The COD task consisted of a 10-m linear sprint followed by a 90° sidestep cut to the either the left or right and followed by a 3-m linear sprint. Although a minimum of 5-m after a COD plant step are a more common COD task (Havens et al., 2015; Jones et al., 2016a; Stewart et al., 2014), a 5-m linear sprint after the cut was not provided due to space limitation of the laboratory. A layout for the COD task to the left is shown in Figure 1. A sidestep cut was described to the participant as using the leg opposite to the direction of movement to move to push-off and using the other leg for the first step in the new direction (Andrew 1977). The participants spent an additional 30-minutes familiarising themselves with the COD task during session one before data collection began. A standardised 10-minute dynamic warm-up preceded the familiarisation during session one and session two. The familiarisation consisted of five COD trials for each direction with increasing running velocity (50%-75%-90%-90%-100%) of their perceived maximum. Familiarisation trials were completed on the participants' self-declared preferred leg ~~plant step~~ to plant and push off; participant's preference was declared after they were shown the COD layout. A five-minute rest was provided prior to familiarisation trials of the non-preferred leg plant step. The participants rested for 10-minutes after the familiarisation trials before starting the testing session. COD trials consisted of three trials using their self-declared preferred plant foot followed by three trials using the non-preferred plant foot. A 2-minute rest was provided between trials for the same direction cut, and a 5-minute rest was inserted between the preferred and non-preferred leg trials. The testing took place in an indoor laboratory with an artificial flooring (Mondo S.p.A., Alba, Italy). During all trials the instructions to the participants were standardised, for example a COD to the left was "sprint maximally for 10-meters, plant and cut with your right leg and sprint maximally to the end." For the trial to be deemed valid, the participants must have whole foot contact on the force plates during deceleration. This was visually inspected by the investigator as well as checking the GRF data after each trial. Participants were allowed to choose their own starting position in order to accommodate different stride patterns needed to perform the sidestep cut on the last force plate with the pre-determined leg (Dos'Santos et al., 2016).

The present study used the 1-1 m time as an indicator of COD ability. The 1-1 m time was measured by single beam photocell timing gates, with digital post-processing to remove false signals, (Smartspeed, Fusion Sports, Coopers Plain, Australia) placed 1-m before the COD step and 1 m after the COD step (Figure 1). The total time of the COD task was also measured by timing gates placed at the start and finish lines of the COD task. Position of the timing gates were set to the hip height of the participants to ensure that only the lower body or trunk triggered the time. The plant leg that resulted in a faster 1-1 m COD was defined as the dominant leg (DL) whereas the side with the slower 1-1 m COD was non-dominant leg (NDL) (Nimphius et al., 2016; Sayers, 2015).

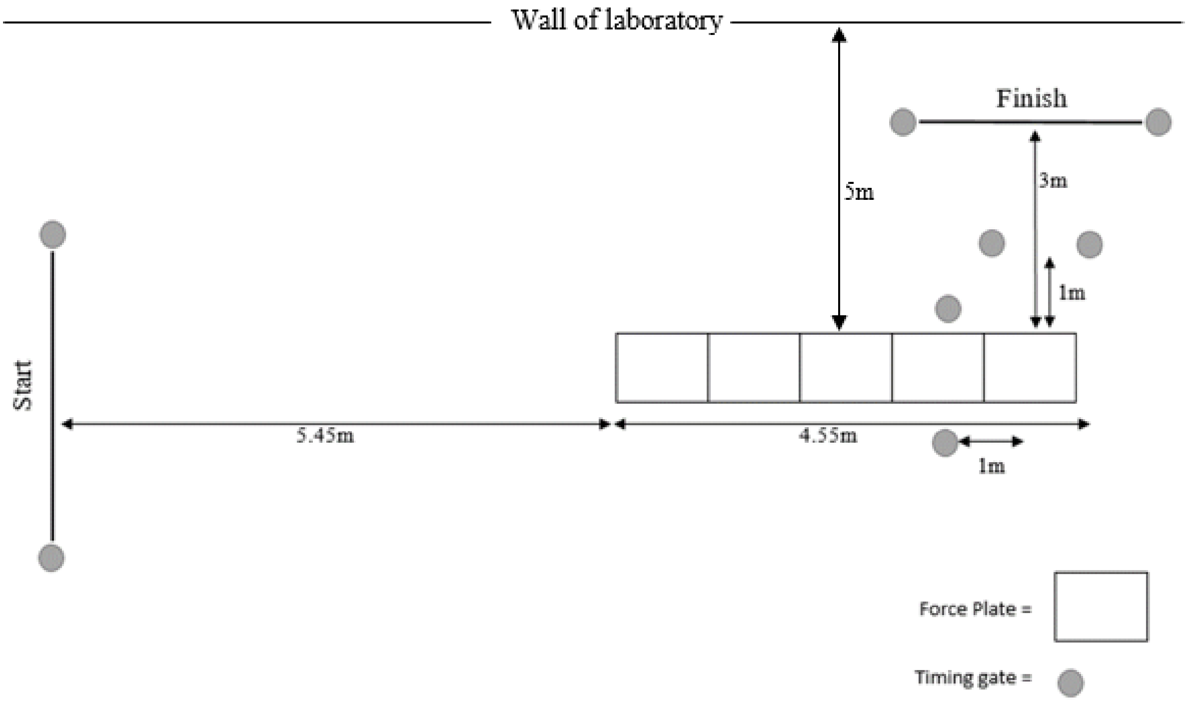

Figure 1. Layout of the COD task

Note: Black lines represent the start and finish of the COD task, and grey circles represent the position of the timing gates, which are located at the start and finish as well as 1-m before and after the COD. The diagram above is for the 90° cut to the left. For the right cut, only the timing gates position were mirrored. The distance of the force plates to the laboratory wall is also 5-m on opposite side of the force plates.

Five in-ground three-dimensional force plates (two TYPE 9287BA and three TYPE 9287CA, Kistler Instruments, Winterthur, Switzerland) were used to collect GRF data during the deceleration of the COD task. GRF data from the force plates were recorded at 960 Hz using the force plate software (Bioware version 5.3.0.7, Kistler Instruments, Winterthur, Switzerland). The start of deceleration was defined as the first step with no propulsive force. However, if no such step was identified then the first step at which a net negative horizontal impulse (calculated as horizontal propulsive impulse – horizontal braking impulse) was chosen as the start of deceleration. Braking steps during deceleration were described with reference from the COD plant step, for example a deceleration that consisted of three braking steps were ordered as such, plant step > penultimate step (PEN) > one step prior to PEN (PEN-1) > two steps prior to PEN (PEN-2). All braking steps were recorded but only steps PEN and PEN-1 were used for analysis, since all participants had at least two braking steps. The peak force, impulse and contact time for PEN and PEN-1 were determined by the force-time curve on the force plate software. All force and impulse variables were calculated relative to body mass (kg) with initial heel contact defined as the instance vertical GRF exceeded 10 N and toe off when vertical GRF dropped below 10 N (Spiteri et al., 2013). As braking is assumed to occur in the sagittal plane during this type of COD (Jones et al, 2016a), only the anterior-posterior GRF were used to quantify braking at PEN and PEN-1. Impulses were determined as the area under the force-time curve. Peak braking was quantified as minimum anterior-posterior GRF force (Fy) and braking impulse was quantified as net area (horizontal braking impulse area - horizontal propulsive impulse area) under the Fy force-time curve for braking steps PEN and PEN-1. However, at the plant step, braking GRF was calculated as the resultant of the medio-lateral and anterior-posterior GRF based on the Fx and Fy force time curve (resultant = $\sqrt{Fx^2 + Fy^2}$) (Dos'Santos et al., 2016) from the heel strike to the minimum of the mid-support phase, and propulsive GRF was determined as vertical GRF based on the Fz force time curve from minimum of mid support phase to toe off. In addition, the difference in braking impulse during PEN-1 and PEN (Δ PEN-1 - PEN) as well as PEN and final (Δ PEN - FIN) were also calculated to examine the braking strategies between faster and slower participants (Dos'Santos et al., 2016). All GRF data were normalised to body mass. As the purpose of this study is to examine the braking associated with COD performance and not average movement pattern, only the fastest trial and associated braking GRF were used for subsequent analyses to obtain data associate with the best performance.

2.3.2 Centre of mass velocity measurement

Centre of mass (COM) displacement was determined with a wearable inertial measurement system (XSENS) (MVN Link, XSENS Technology, Enschede, The Netherlands) to determine the velocity during PEN -1 step and plant step. The participants wore a lycra suit that housed 17 inertial sensors (0.038 x 0.053 x 0.021 m, 0.03 kg) and data was collected and processed using the XSENS recording software (MVN Studio Version 3.5.3, XSENS Technology, Enschede, The Netherlands). The force plates and XSENS recording were time synchronised through an analogue board which allowed the force plate software to trigger the start of data capture within the XSENS software. Sampling frequency of 960 Hz was selected for the force plates to match the maximum 120 Hz sampling frequency of XSENS (Callaghan et al., 2018). A static calibration using a stationary N-pose (quiet standing with hands alongside the body) was performed prior to testing according to manufacturer recommendations. Re-calibration was performed when battery for the sensors needed to be replaced, no further calibrations were required during the testing. The XSENS motion analysis system has been found to be reliable and valid in measuring position (Kok et al., 2014; Zhang et al., 2013). The COM displacement was exported to Microsoft Excel (Microsoft Office 365, Redmond, WA) and a second order low pass Butterworth filter with a cut-off frequency of 3 Hz (as determined by a fast Fourier transform) was applied. COM displacement data was differentiated using finite differences method to calculate COM velocity. COM entry velocity was determined by the average of velocities 10 frames prior to the start of PEN-1 to 10 frames after toe off of PEN-1 whereas COM exit velocity was calculated from 10 frames prior to mid-support phase to 10 frames after toe off of the vertical GRF force-time curve of the plant step as modified from prior studies (Jones et al., 2017).

2.3.3 Drop jump reactive strength index

Drop jumps from a 20, 40 and 60 cm box were performed on to a contact mat (Swift Performance Equipment, Lismore, Australia) to determine contact time and flight time. Jump heights were performed in a randomised order. Participants held a carbon fibre pole across their shoulders to restrict arm movement (Markwick et al., 2015). Instructions to the participants for the drop jump were to step off (not jump off) the box with their preferred leg and “jump as high as possible and as fast as possible”. For the trial to be valid, the participant had to drop, not jump from the box and was required to land with both feet on the contact mat each trial and have a contact time of less than 250 milliseconds (Markwick et al., 2015). Participants were required to repeat the jump if contact time was higher than 250 milliseconds. Contact times of all participants for 20, 40 and 60 cm drop jumps were 206.14 ± 11.72, 210.81 ± 11.84 and 229.57 ± 9.31 milliseconds respectively. Jump height determined by the formula (9.81 x flight time^2 / 8). RSI was calculated by dividing jump height by contact time (Lockie et al., 2014b). Three trials were performed and the highest RSI of the trials for each jump height was used for analysis.

2.3.4 Unilateral Leg press concentric and eccentric 1RM assessment

Maximal unilateral strength in the leg press was determined concentrically and eccentrically. Participants performed the assessment using a modified leg press machine (Cybex Leg Press; Cybex International, Medway, MA, USA) with a winch attached to the top of the frame to raise the weight at the top position for eccentric only strength assessment. The leg press method was adapted from previous study that utilised a similar set up (Walker et al., 2016). Participants performed the first warm-up set on the leg press bilaterally for 5-10 repetition at 40-60% of the participant's perceived maximum. Participants then rested for 3 minutes before performing another warm-up set of 3-5 repetitions of bilateral leg press at 60-80% of their perceived maximum. The weight used bilaterally for the second warm-up set was also used as the starting weight for concentric unilateral leg press. Starting weight of 60-80% bilateral perceived max was used based on prior pilot testing to select a suitable starting weight to reach 1RM within three to five attempts (Haff and Triplett., 2015). The participants rested for 3 minutes before starting the unilateral concentric leg press 1RM assessment. From this point the weight was increased 5 % to 10 % or according to the participant's perceived ability until 1RM is reached (Haff et al., 2015). The weight was held by the investigators and lowered until the participant's knee angle was 90° then the participant pushed the weight until full extension. A minimum three-minute rest separated each 1RM attempt. A maximum of five attempts was used to achieve a 1RM. The heaviest load before failure was recorded as the 1RM (Haff and Triplett., 2015; McBride et al., 2002). The same protocol was followed to determine the 1RM of the non-preferred leg.

After the concentric protocol was completed, the participant rested for 5 minutes before starting the eccentric protocol. The eccentric protocol started at 120% of the maximal unilateral concentric load of the same leg during concentric trials. For eccentric protocol the weight was required to be lowered to a 90° knee angle at a 3-s cadence. Cadence was controlled by a metronome and markers on the leg press to show the distance of lowering required every second at an isoinertial cadence (Walker et al., 2016). If the participant lowers the weight too fast or held the weight isometrically at certain segments, the trial was considered a failed attempt. The participant performed one repetition at each load with three to five-minutes rest between loads (Hollander et al., 2007). Weight was continually increased as that described in the concentric protocol. The maximum load of the concentric and eccentric protocol was made relative to the participant's body mass and used for analysis.

2.3.5 Leg curls concentric and eccentric 1RM assessment

Maximal unilateral strength in the leg curl was determined concentrically and eccentrically A prone leg curl machine (Cybex Prone Leg Curl; Cybex International, Medway, MA, USA) was used to assess knee flexor 1RM. The protocol and progression of weight was the same as described during leg press. Participants were required to lift to the end range of motion during concentric knee flexion assessment (Potier et al., 2009), which was used as the starting point for eccentric assessment. During eccentric assessment, participants started lowered the weight at a three seconds cadence until full knee extension.

2.3.6 Isokinetic and isometric strength assessment

Maximal isometric and isokinetic torque of the knee extensors and flexors were measured by a dynamometer (Biodex System 3, Biodex Medical, Shirley, New York) and data were recorded with the provided manufacturer software (Biodex System 3 Advantage Software, Biodex Medical, Shirley, New York). The isometric torque was measured at knee angle at 60°of knee flexion. For isokinetic measurement, two angular velocities of $90°\cdot s^{-1}$ and $180°\cdot s^{-1}$ were used for the range of motion from 90° to 0° (full extension) for concentric and eccentric strength assessment. Participants were tested in the following order, isometric extensors, isometric flexors, isokinetic concentric extensors, isokinetic concentric flexors, isokinetic eccentric extensors and isokinetic eccentric flexors. The centre of rotation of the knee was aligned to the centre of rotation of the lever arm of the dynamometer. Participants were seated upright with hip joint at approximately 90°. Extraneous movement of participant was secured with a crossover and waist strap while lateral movement of the leg was secured with a thigh and ankle straps. Participants completed two warm-up sets of four submaximal contractions (50%, 50%, 80% and 95% of perceived maximum). Each warm-up set consisted of, five seconds isometric efforts of the knee extensors and flexors, and $90°\cdot s^{-1}$ isokinetic concentric efforts of knee extensors and flexors. Participants rested for one minute between isometric and isokinetic contractions during the warm-up set as well as between warm-up sets. Three minutes' rest was provided after the warm-up before starting the test. Gravity corrections for limb mass were performed prior to every isometric and isokinetic test. The lever arm of the dynamometer was fixes at 45° knee flexion and participants were asked to completely rest their limb on lever arm, static limb weight was then recorded into the dynamometer software for gravity correction. Participants were instructed to perform each trial maximally and were verbally encouraged throughout every repetition of each test. During isometric testing, participant contracted their knee extensors (push) maximally against a stationary lever arm for five seconds followed by a five second rest before contracting knee flexors (pull) for five seconds. Participants performed two isometric contractions for both knee extensors and flexors and rested for two minutes before performing another two contractions. Isokinetic concentric test was performed in succession, starting with the knee extensors followed immediately by knee flexors, at angular velocities of $180°\cdot s^{-1}$ first followed by $90°\cdot s^{-1}$ after a two-minute rest. The higher angular velocity was performed first during concentric trials as there was less time under tension and therefore less fatigue was expected. Isokinetic eccentric strength of the knee extensors and flexors were tested individually at an angular velocity of $90°\cdot s^{-1}$ for both extensors and flexors first before performing $180°\cdot s^{-1}$. The peak torque and angle where peak torque occurred during isokinetic testing were visually identified from the software's graphical output. Only the highest torque value and angle that it occurred during the testing velocity was recorded. The highest peak torque value was made relative to bodyweight and used for analysis.

2.4 Statistical analyses

Mean and standard deviation was calculated for all variables. Inter-day reliability of COD 1-1 m time, total time, were assessed using paired-sample t-test, intraclass correlation (ICC) with 95% confidence interval (95% CI), typical error of measurement (TEM), and coefficient of variation (CV %) with 95% CI from two separate days. the magnitude of the ICC was assessed based on the threshold values 0.1, 0.3, 0.5, 0.7, 0.9, and 1.0 for low, moderate, high, very high, nearly perfect, and perfect (Hopkins et al., 2009). A CV of ≤ 10% was set as the threshold criterion for acceptable reliability (Cormack et al., 2008). All data were tested for normality using a Shapiro–Wilk test.

Faster (n = 10) and slower (n = 10) groups were determined by the 1-1 m COD time during DL and NDL, the middle two participants were excluded using similar methodology to prior studies(Dos'Santos et al., 2016; Nimphius et al., 2016; Spiteri et al., 2013). In addition, participants from the faster and slower groups were pooled together for DL and NDL comparison (n = 20). A two-way ANOVA (step x group) was used to determine if differences exist in braking impulse during plant, PEN and PEN-1 steps (step) between faster and slower (group) COD on both DL and NDL. To provide an indication of braking strategy between faster and slower participants, difference in braking impulse from PEN-1 to PEN and PEN to plant were calculated for both DL and NDL COD. Lastly, eccentric and concentric isokinetic strength ratio as well as eccentric and isometric strength ratio were calculated to observe if faster participants have greater eccentric strength relative to concentric strength. Independent sample t-tests and Hedges' *g* effect size were also used to assess the differences and magnitude of differences of GRF during each step and muscle function between groups with sequential Bonferroni corrections (Holm, 1979) to reduce type I errors. The magnitude of effect size was interpreted following Hopkins et al. (2009) guideline, with trivial = < 0.19; small = 0.2 - 0.59; moderate = 0.6 – 1.19; large = 1.2 – 1.99; very large = 2.0 - 4.0. Paired sample t-test was used to compare pooled DL and NDL COD with Hedges' *g* effect size and sequential Bonferroni corrections for multiple comparison on the same dependent variables as faster and slower group comparisons.

Pearson's correlation (r) with 95% CI and coefficient of determination (R^2) were used to examine the relationship between GRF variables, muscle function and 1-1 m COD time of all twenty-two participants with sequential Bonferroni corrections (Holm, 1979) to reduce type I errors. Muscle function of DL and NDL were used in the correlation analyses with DL and NDL COD performance and GRF. Muscle function and GRF correlations were made with the respective leg for COD plant step, for example, if the participant DL COD was made with their right leg at the plant step. The strength of correlations were described as follows small (0.10 – 0.29), moderate (0.30 – 0.49), large (0.50 – 0.69), and very large (0.70 – 0.89), nearly perfect (0.90 – 0.99), and perfect (1.0) (Hopkins, 2000). The level of significance for all statistical analyses were set at $p \leq 0.05$. All statistical analysis was performed with SPSS Statistics (Version 23, IBM Inc., USA).

Chapter 3. RESULTS

3.1 Reliability of COD performance measures

Table 1 shows the test-retest reliability for COD performance based on total time and 1-1 m COD time for the DL and NDL. Paired t-test revealed no statistical differences in DL (p = 0.055 – 0.063) but significant differences (p = 0.015 – 0.029) in NDL total time and 1-1 m COD performance between-sessions. However, the DL and NDL 1-1 m COD time demonstrated good reliability with very high ICC and acceptable CV% (Table 1.)

Table 1. Between-session reliability for COD total time and 1-1m COD time for DL and NDL.

	Session 1 Mean ± SD	**Session 2 Mean ± SD**	***p***	**ICC (95% CI)**	**CV (95% CI)**	**TEM**
DL Total time (s)	2.76 ± 0.14	2.73 ± 0.15	0.063	0.831 (0.648 - 0.923)	2.2% (1.8 – 3.4%)	0.06
DL 1-1m time (s)	0.23 ± 0.03	0.22 ± 0.04	0.055	0.769 (0.537 - 0.893)	7.7% (5.4 – 10.3%)	0.02
NDL Total time (s)	2.81 ± 0.17	2.78 ± 0.16	0.015	0.754 (0.510 - 0.885)	1.4% (1.2 – 2.1%)	0.04
NDL 1-1m time (s)	0.28 ± 0.06	0.27 ± 0.05	0.029	0.850 (0.707 - 0.922)	9.3% (7.1 – 13.6%)	0.02

Note: Session 1 and session 2 were separated by 24 hours. The results of paired t-test to compare between-session 1 and session 2, and ICC with 95% CI, CV with 95% CI and TEM of the two sessions are shown. DL = Dominant leg, NDL = Non-dominant leg, ICC = Intraclass correlation, CV = Coefficient of variation, TEM = Typical error measurement.

3.2 Comparison of faster and slower participants

3.2.1 COD performance

3.2.1.1 Dominant leg COD total time, 1-1 m COD time, entry and exit velocity comparisons

Table 2 shows 1-1 m COD time, total time, entry and exit velocities for faster and slower participants during DL COD. The 1-1 m COD time was significantly shorter in the faster than slower group ($p \leq 0.001$, $g = 2.50$). No significant differences were noted for the total time, entry velocity and exit velocity between faster and slower DL COD groups.

Table 2. Mean ± SD comparison of COD total time, 1-1 m COD time, entry velocity and exit velocity between dominant leg (DL) faster and slower participants.

COD performance	**DL Faster (n = 10)**	**DL Slower (n = 10)**	***p***	***g***	***Effect Size magnitude descriptor***
Total time (s)	2.69 ± 0.10	2.78 ± 0.16	0.135	0.67	Moderate
1-1 m COD time (s)	0.19 ± 0.02 **	0.24 ± 0.02	≤ 0.001	2.50	Very large
Entry velocity (m·s-^{1})	4.57 ± 1.01	4.22 ± 1.38	0.518	0.29	Small
Exit velocity (m·s^{-1})	3.16 ± 0.38	3.12 ± 0.63	0.873	0.08	Trivial

*Note: Comparisons between faster and slower DL groups measured by independent t-test (significance p ≤ 0.05). * p ≤ 0.05, ** p ≤ 0.01*

3.2.1.2 Non-dominant COD total time, 1-1 m COD time, entry and exit velocity comparisons

Table 3 shows 1-1 m COD time, total time, entry and exit velocities for faster and slower participants during NDL COD. The 1-1 m COD time was significantly lower in the faster than slower group ($p \leq 0.001$, $g = 2.85$). No significant differences were noted for the total time, entry velocity and exit velocity between faster and slower NDL COD groups.

Table 3. Mean ± SD comparison of COD total time, 1-1 m COD time, entry velocity and exit velocity between non-dominant leg (NDL) faster and slower participants.

COD performance	**NDL Faster (n = 10)**	**NDL Slower (n = 10)**	***p***	***g***	***Effect Size magnitude descriptor***
Total time (s)	2.72 ± 0.13	2.82 ± 0.16	0.137	0.69	Moderate
1-1 m COD time (s)	0.22 ± 0.02 **	0.31 ± 0.04	≤ 0.001	2.85	Very large
Entry velocity ($m \cdot s^{-1}$)	4.54 ± 1.33	4.06 ± 1.23	0.513	0.37	Small
Exit velocity ($m \cdot s^{-1}$)	2.78 ± 0.73	2.61 ± 0.66	0.603	0.24	Small

*Note: Comparisons between faster and slower DL groups measured by independent t-test (significance $p \leq 0.05$). * $p \leq 0.05$, ** $p \leq 0.01$*

3.2.1.3 Pooled dominant and non-dominant leg COD total time, 1-1 m COD time, entry and exit velocity comparisons

Table 4 shows 1-1 m COD, total time, entry and exit velocities for DL and NDL COD. The 1-1 m COD time was significantly lower in the DL COD than NDL COD ($p \leq 0.001$, g = 1.41). No significant differences were noted for the total time, entry velocity and exit velocity between pooled DL and NDL COD groups.

Table 4. Mean ± SD comparison of COD total time, 1-1 m COD time, entry velocity and exit velocity between pooled dominant leg (DL) and non-dominant leg (NDL) COD.

COD performance	**Pooled DL (n = 20)**	**Pooled NDL (n = 20)**	***p***	**g**	***Effect Size magnitude descriptor***
Total time (s)	2.74 ± 0.14	2.78 ± 0.14	0.051	0.29	Small
1-1 m COD time (s)	0.21 ± 0.03 **	0.26 ± 0.04	≤ 0.001	1.41	Large
Entry velocity ($m \cdot s^{-1}$)	4.39 ± 1.19	4.30 ± 1.13	0.785	0.10	Trivial
Exit velocity ($m \cdot s^{-1}$)	2.91 ± 0.51	2.86 ± 0.57	0.810	0.09	Trivial

*Note: Comparisons between DL and NDL COD measured by paired sample t-test (significance $p \leq 0.05$). * $p \leq 0.05$, ** $p \leq 0.01$*

3.2.2 Ground reaction force during COD

3.2.2.1 Dominant leg COD ground reaction force comparisons

No significant differences in GRF during the last three steps were observed between the faster and slower DL COD groups as shown in Table 5. Furthermore, individual propulsive impulse and braking impulse of the plant, PEN and PEN-1 illustrated in Figure 2 shows GRF application were similar between faster and slower participants during DL COD.

Table 5. Mean ± SD comparison of ground reaction force of the last three steps between dominant leg (DL) faster and slower participants.

Body mass normalised impulse (m·s-1)	**DL Faster (n = 10)**	**DL Slower (n = 10)**	**p**	**g**	**Effect Size magnitude descriptor**
Plant propulsive impulse (Fz)	2.45 ± 0.44	2.40 ± 0.53	0.809	0.10	Trivial
Plant resultant braking (Fh)	0.71 ± 0.26	0.52 ± 0.17	0.062	0.86	Moderate
PEN braking impulse (Fy)	-1.11 ± 0.20	-0.96 ± 0.18	0.092	0.79	Moderate
PEN-1 braking impulse (Fy)	-0.61 ± 0.25	-0.76 ± 0.19	0.159	0.68	Moderate

*Note: plant step propulsive (Fz), plant step resultant braking (Fh), penultimate (PEN) step braking (Fy) and one step prior to penultimate (PEN-1) step braking (Fy) ground reaction force. Resultant braking calculated as $Fh = \sqrt{Fx^2 + Fy^2}$ with Fx being medial-lateral force and Fy being anterior-posterior force. * $p \leq 0.05$, ** $p \leq 0.01$*

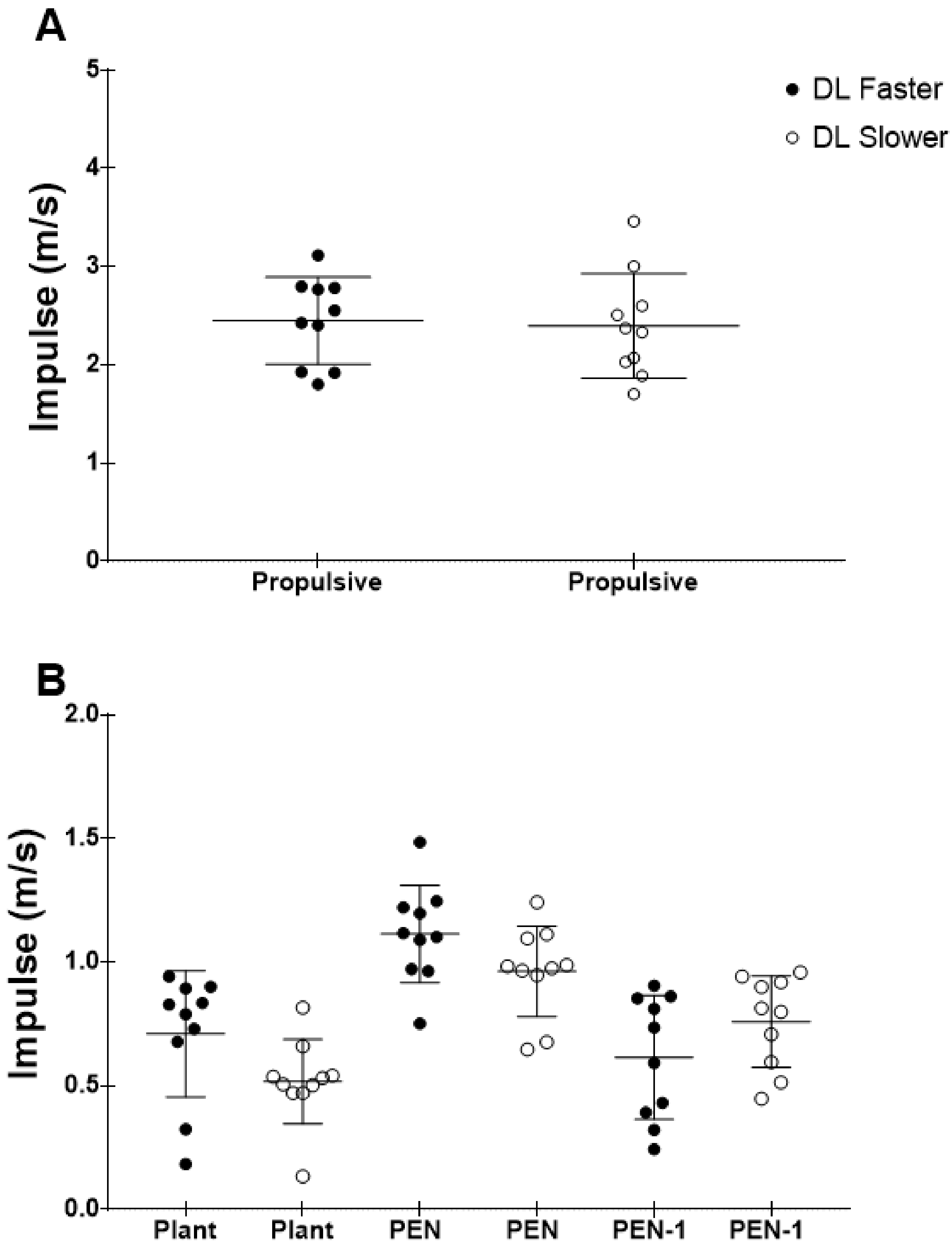

Figure 2. Individual data point with mean and SD presented between DL (dominant leg) faster and slower groups.

Note: Comparison of (A) bodyweight normalised plant step propulsive impulse and (B) bodyweight normalised braking impulse during the COD plant step, penultimate step (PEN) and one step prior to penultimate step (PEN-1) are shown. Negative impulses are inverted to show values above the x-axis. No significance differences between DL faster and slower groups were observed.

3.2.2.2 Non-dominant leg COD ground reaction force comparisons

No significant differences in GRF during the last three steps were noted between the faster and slower NDL COD group as shown in Table 6. Furthermore, individual propulsive impulse and braking impulse of the plant, PEN and PEN-1 illustrated in Figure 3 shows GRF application were similar between faster and slower participants during NDL COD

Table 6. Mean ± SD comparison of ground reaction force of the last three steps between non-dominant leg (NDL) faster and slower participants.

Body weight normalised impulse (m·s-1)	**NDL Faster (n = 10)**	**NDL Slower (n = 10)**	***p***	***g***	***Effect Size magnitude descriptor***
Plant propulsive impulse (Fz)	2.75 ± 0.33	2.90 ± 0.55	0.463	0.33	Small
Plant resultant braking (Fh)	0.46 ± 0.26	0.51 ± 0.21	0.628	0.21	Small
PEN braking impulse (Fy)	-1.06 ± 0.31	-0.95 ± 0.23	0.365	0.40	Small
PEN-1 braking impulse (Fy)	-0.65 ± 0.28	-0.67 ± 0.25	0.877	0.07	Moderate

Note: plant step propulsive (Fz), plant step resultant braking (Fh), penultimate (PEN) step braking (Fy) and one step prior to penultimate (PEN-1) step braking (Fy) ground reaction force. Resultant braking calculated as $Fh = \sqrt{Fx^2 + Fy^2}$ *with Fx being medial-lateral force and Fy being anterior-posterior force. * $p \leq 0.05$, ** $p \leq 0.01$*

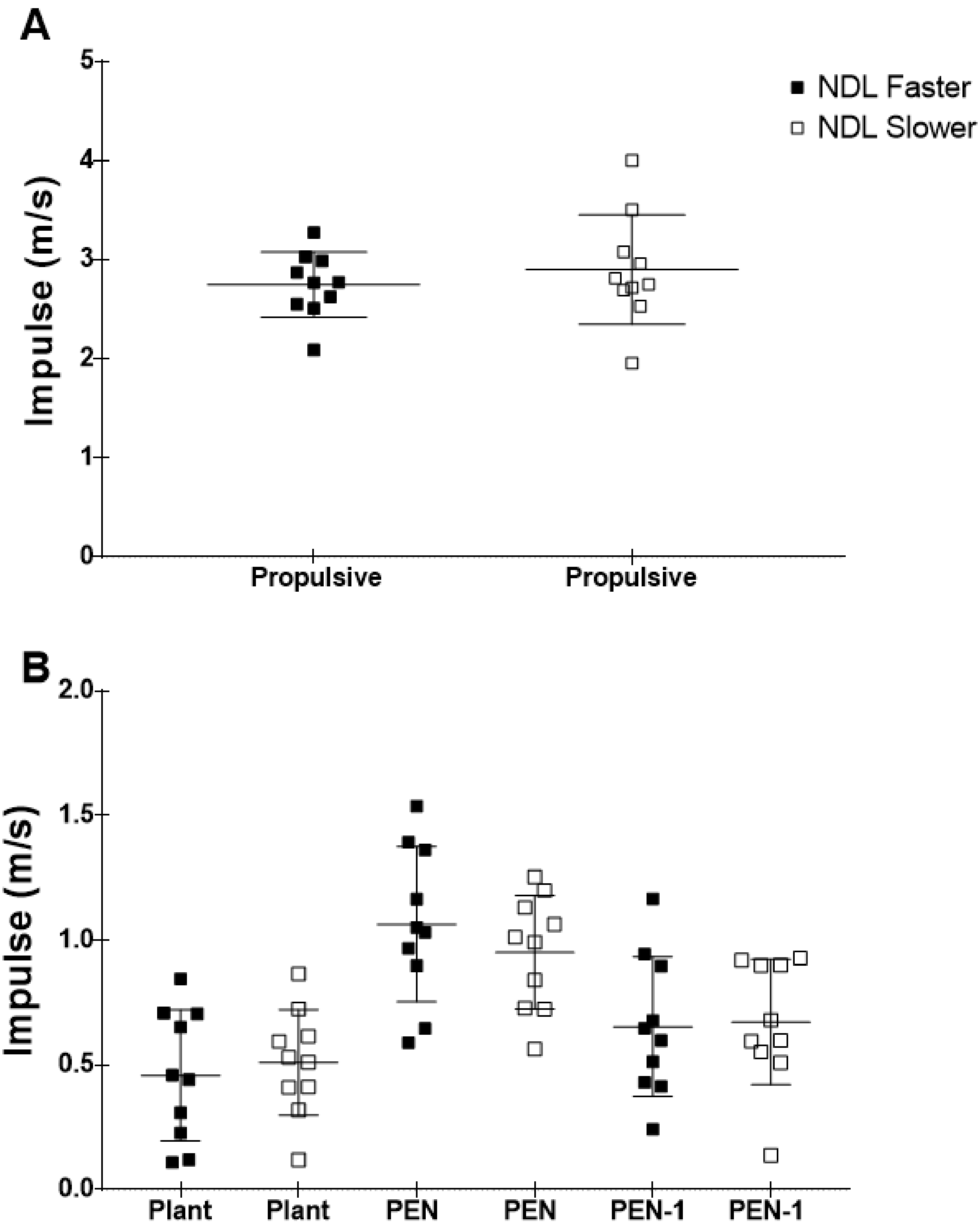

Figure 3. Individual data point with mean and SD presented between NDL (non-dominant leg) faster and slower groups.

Note: Comparison of (A) body mass normalised plant step propulsive impulse and (B) body mass normalised braking impulse during the COD plant step, penultimate step (PEN) and step prior to penultimate step (PEN-1) are shown. Negative impulses are inverted to show values above the x-axis. No significance differences between NDL faster and slower groups were observed.

3.2.2.3 Pooled dominant and non-dominant leg ground reaction force comparisons

Significant differences were observed at the plant step propulsive impulse and plant step resultant braking impulse between the DL and NDL COD for GRF during the last three steps. Participants during DL COD had significantly lower mean plant step propulsive and mean resultant braking impulse (Table 7). However, Figure 4 shows many of the individual plant propulsive and plant braking impulse values are similar between DL and NDL COD despite significant difference in the mean values.

Table 7. Mean ± SD comparison of ground reaction force of the last three steps between pooled dominant leg (DL) and non-dominant leg (NDL) COD.

Body mass normalised impulse ($m \cdot s^{-1}$)	**DL (n = 20)**	**NDL (n = 20)**	***p***	***g***	***Effect size magnitude descriptor***
Plant propulsive impulse (Fz)	2.42 ± 0.47 *	2.77 ± 0.47	0.008	0.74	Moderate
Plant resultant braking (Fh)	0.61 ± 0.23 *	0.47 ± 0.23	0.043	0.61	Moderate
PEN braking impulse (Fy)	-1.04 ± 0.20	-1.05 ± 0.26	0.828	0.04	Trivial
PEN-1 braking impulse (Fy)	-0.69 ± 0.22	-0.68. ± 0.25	0.859	0.04	Trivial

*Note: plant step propulsive (Fz), plant step resultant braking (Fh), penultimate (PEN) step braking (Fy) and one step prior to penultimate (PEN-1) step braking (Fy) ground reaction force. Resultant braking calculated as $Fh = \sqrt{Fx^2 + Fy^2}$ with Fx being medial-lateral force and Fy being anterior-posterior force. * $p \leq 0.05$, ** $p \leq 0.01$*

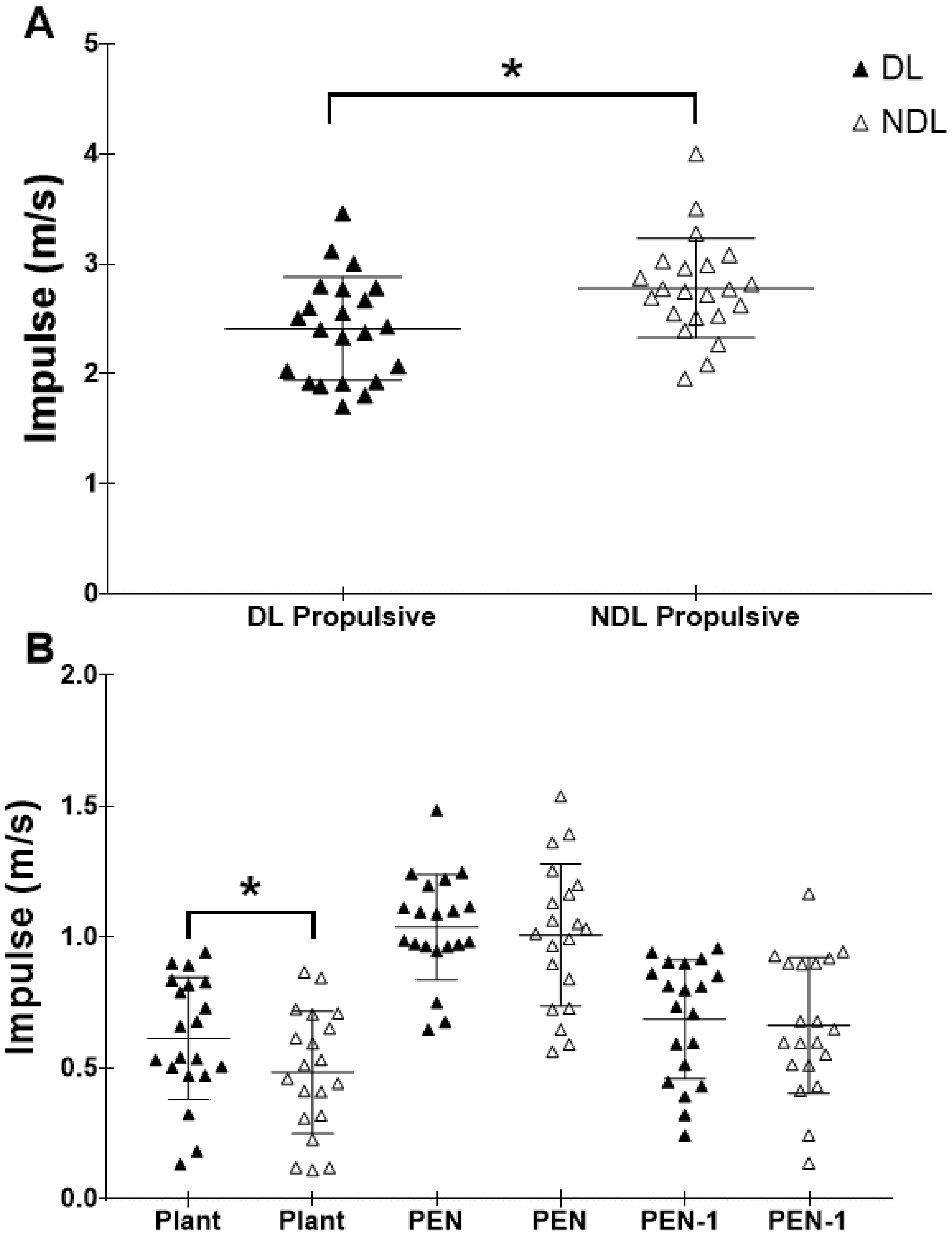

Figure 4. Individual data point with mean and SD presented between DL (dominant leg) and NDL (non-dominant leg) groups.

Note: Comparison of (A) bodyweight normalised propulsive impulse and (B) bodyweight normalised braking impulse during the COD plant step, penultimate step (PEN) and step prior to penultimate step (PEN-1) are shown. Braking impulse are inverted to compare values above the x-axis. * $p \leq 0.05$

3.2.3 Braking strategies during COD

Figure 5 illustrates the change in braking impulse from PEN-1 to PEN step and from PEN to plant step. A significant interaction effect ($F(2, 54) = 3.865$, $p = 0.027$) was observed between faster and slower participants during DL COD but no significant interaction was observed between faster and slower participants during NDL COD. Table 9 shows the mean and SD in the change in braking impulse of both faster and slower groups during DL and NDL COD. Comparison of the change in braking impulse revealed faster DL COD participants had significantly higher change in braking impulse from the PEN-1 and PEN step but no significant difference was observed between the PEN and plant step. No significant differences in change in braking impulse differences were noted between faster and slower participants during NDL COD among all braking steps.

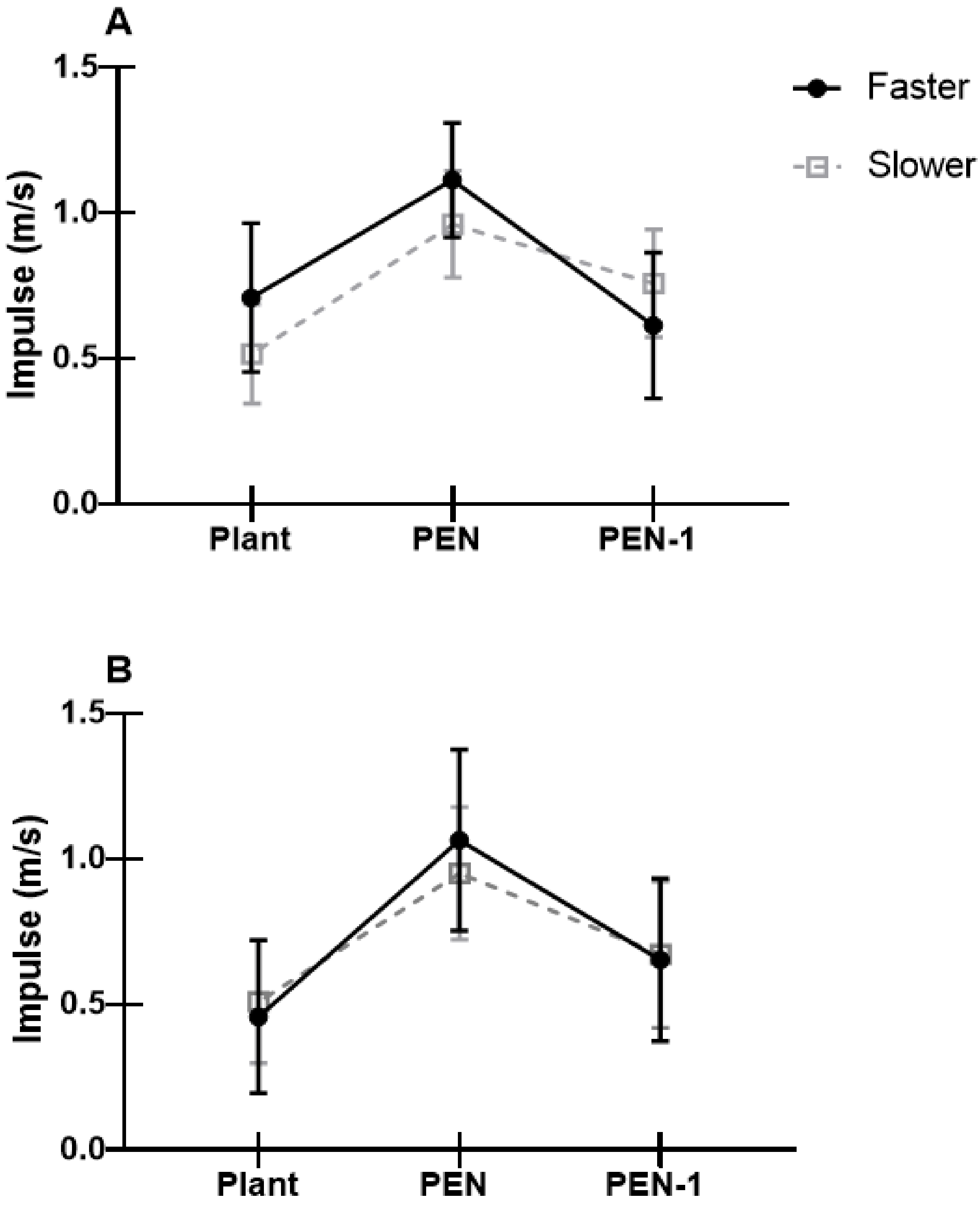

Figure 5. Comparison of mean braking impulse during the last three steps between faster and slower participants during (A) dominant leg COD and (B) non-dominant leg COD.

Note: Last three steps were plant, penultimate (PEN) and step prior to penultimate (PEN-1). A significant interaction effect was observed for faster dominant leg COD participants (A), $F\ (2, 54) = 3.865$, $p = 0.027$.

Table 8. Mean ± SD comparison of the change in braking impulse between braking steps (braking strategy) of last three steps between faster and slower groups during dominant leg (DL) and non-dominant leg (NDL) COD.

Braking strategy	**Faster (n = 10)**	**Slower (n = 10)**	***p***	***g***	***Effect Size magnitude descriptor***
DL Δ PEN-1 – PEN ($m \cdot s^{-1}$)	-0.50 ± -0.31*	-0.20 ± -0.15	0.013	1.23	Large
DL Δ PEN – Plant ($m \cdot s^{-1}$)	0.40 ± 0.37	0.45 ± 0.28	0.779	0.15	Trivial
NDL Δ PEN-1 – PEN ($m \cdot s^{-1}$)	-0.41 ± -0.37	-0.28 ± -0.26	0.356	0.41	Small
NDL Δ PEN – Plant ($m \cdot s^{-1}$)	0.61 ± 0.44	0.44 ± 0.34	0.364	0.43	Small

Note: Braking strategy assessed by the change in braking impulse between the penultimate step (PEN) and one step prior to penultimate step (PEN-1) as well as PEN and plant step. Comparisons between faster and slower groups measured by independent t-test. * $p \leq 0.05$, ** $p \leq 0.01$

3.2.4 Muscle function comparisons

3.2.4.1 Dominant leg muscle function comparisons

No significant differences in any muscle function variables were noted between faster and slower DL COD participants as shown in Table 9. Additionally, there were no significant differences in isokinetic eccentric and concentric strength ratios for all isokinetic velocities, $90^{o} \cdot s^{-1}$ and $180^{o} \cdot s^{-1}$, for both knee extensors and knee flexor as shown in Table 10 and Table 11.

Table 9. Mean ± SD comparison of muscle function variables between dominant leg (DL) faster and slower participants.

	DL Faster (n = 10)	DL Slower (n = 10)	*p*	*g*	*Effect Size magnitude descriptor*
Drop jump reactive strength index					
20 cm	1.31 ± 0.31	1.43 ± 0.41	0.471	0.33	Small
40 cm	1.43 ± 0.33	1.54 ± 0.52	0.579	0.25	Small
60 cm	1.47 ± 0.34	1.47 ± 0.47	0.919	0.02	Trivial
Leg press and leg curl 1RM					
Leg press CON 1RM ($kg \cdot BM^{-1}$)	1.14 ± 0.19	1.33 ± 0.30	0.062	0.75	Moderate
Leg press ECC 1RM ($kg \cdot BM^{-1}$)	1.49 ± 0.33	1.73 ± 0.52	0.167	0.55	Small
Leg curl CON 1RM ($kg \cdot BM^{-1}$)	0.55 ± 0.06	0.57 ± 0.09	0.663	0.26	Small
Leg curl ECC 1RM ($kg \cdot BM^{-1}$)	0.69 ± 0.12	0.71 ± 0.16	0.702	0.14	Trivial
Isometric and isokinetic torque					
ISO EXT ($Nm \cdot BM^{-1}$)	3.37 ± 0.42	3.17 ± 0.71	0.464	0.34	Small
ISO FLX ($Nm \cdot BM^{-1}$)	1.77 ± 0.25	1.63 ± 0.26	0.243	0.55	Small
CON $90^o \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	2.82 ± 0.30	2.68 ± 0.45	0.451	0.37	Small
CON $90^o \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	1.57 ± 0.17	1.41 ± 0.16	0.060	0.97	Moderate
CON $180^o \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	2.22 ± 0.28	2.14 ± 0.33	0.328	0.26	Small
CON $180^o \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	1.37 ± 0.18	1.23 ± 0.14	0.068	0.87	Moderate
ECC $90^o \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	3.22 ± 0.64	3.28 ± 0.70	0.841	0.09	Trivial
ECC $90^o \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	2.29 ± 0.37	2.11 ± 0.35	0.279	0.50	Small
ECC $180^o \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	3.25 ± 0.61	3.11 ± 0.94	0.725	0.18	Trivial
ECC $180^o \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	2.50 ± 0.42	2.13 ± 0.37	0.070	0.93	Moderate

Note: Comparison measured by independent t-test (significance $p \leq 0.05$). BM = Body mass (kg), 1RM = one repetition max, ISO = isometric torque, CON = concentric isokinetic torque, ECC = eccentric isokinetic torque, EXT = knee extensors, FLX = knee flexor. * $p \leq 0.05$, ** $p \leq 0.01$

Table 10. Mean ± SD comparison isokinetic eccentric and concentric torque ratios between dominant leg (DL) faster and slower participants.

ECC : CON ratio	**DL Faster (n = 10)**	**DL Slower (n = 10)**	***p***	***g***	***Effect Size magnitude descriptor***
ECC : CON EXT 90°·s^{-1}	1.14 ± 0.16	1.21 ± 1.38	0.245	0.07	Trivial
ECC : CON FLX 90°·s^{-1}	1.46 ± 0.20	1.49 ± 0.22	0.779	0.14	Trivial
ECC : CON EXT 180°·s^{-1}	1.46 ± 0.21	1.46 ± 0.40	0.998	0.00	Trivial
ECC : CON FLX 180°·s^{-1}	1.81 ± 0.27	1.73 ± 0.24	0.469	0.31	Small

Note: Comparison measured by independent t-test (Significance $p \leq 0.05$). ISO = isometric torque, CON = concentric isokinetic torque, ECC = eccentric isokinetic torque, EXT = knee extensors, FLX = knee flexor. * $p \leq 0.05$, ** $p \leq 0.01$

Table 11. Mean ± SD comparison isokinetic eccentric and isometric torque ratios between dominant leg (DL) faster and slower participants.

ECC : ISO ratio	**DL Faster (n = 10)**	**DL Slower (n = 10)**	***p***	**g**	***Effect Size magnitude descriptor***
ECC 90°·s^{-1} : ISO EXT	0.96 ± 0.14	1.05 ± 0.13	0.168	0.67	Moderate
ECC 90°·s^{-1} : ISO FLX	1.30 ± 0.18	1.30 ± 0.17	0.960	0.00	Trivial
ECC 180°·s^{-1} : ISO EXT	0.96 ± 0.13	0.99 ± 0.21	0.772	0.17	Trivial
ECC 180°·s^{-1} : ISO FLX	1.41 ± 0.25	1.30 ± 0.13	0.251	0.55	Moderate

Note: Comparison measured by independent t-test (Significance $p \leq 0.05$). ISO = isometric torque, CON = concentric isokinetic torque, ECC = eccentric isokinetic torque, EXT = knee extensors, FLX = knee flexor. * $p \leq 0.05$, ** $p \leq 0.01$

3.2.4.2 Non-dominant leg COD muscle function comparisons

Faster NDL COD participants demonstrated significantly greater relative isometric knee flexor strength ($p \leq 0.001$, $g = 1.22$), relative isometric knee extensor strength ($p = 0.017$, $g = 0.34$) and isokinetic concentric 90°s-1 knee extensor strength ($p = 0.03$, $g = 1.27$) (Table 12). However, no significant differences were found between faster and slower NDL COD participants for isokinetic measurements at 180°s-1 as well as other muscle function measures. Additionally, there were no significant differences in isokinetic eccentric and concentric strength ratios for all isokinetic velocities, 90°s-1 and 180°s-1, for both knee extensors and knee flexor as shown in Table 13. and Table 14.

Table 12. Mean ± SD comparison of muscle function variables between non-dominant leg (NDL) faster and slower participants.

	NDL Faster (n = 10)	**NDL Slower (n = 10)**	***p***	**g**	***Effect Size magnitude descriptor***
Drop jump reactive strength index					
20 cm	1.42 ± 0.34	1.25 ± 0.34	0.287	0.50	Small
40 cm	1.58 ± 0.27	1.29 ± 0.49	0.121	0.73	Moderate
60 cm	1.63 ± 0.26*	1.24 ± 0.48	0.042	1.01	Moderate
Leg press and leg curl 1RM					
Leg press CON 1RM ($kg \cdot BM^{-1}$)	1.20 ± 0.19	1.25 ± 0.33	0.684	0.19	Trivial
Leg press ECC 1RM ($kg \cdot BM^{-1}$)	1.51 ± 0.32	1.74 ± 0.37	0.166	0.66	Moderate
Leg curl CON 1RM ($kg \cdot BM^{-1}$)	0.52 ± 0.20	0.60 ± 0.13	0.340	0.47	Small
Leg curl ECC 1RM ($kg \cdot BM^{-1}$)	0.66 ± 0.26	0.71 ± 0.18	0.630	0.22	Small
Isometric and isokinetic torque					
ISO EXT ($Nm \cdot BM^{-1}$)	3.59 ± 0.72 *	2.93 ± 0.32	0.017	1.18	Moderate
ISO FLX ($Nm \cdot BM^{-1}$)	1.94 ± 0.25 *	1.63 ± 0.26	0.005	1.22	Large
CON $90^{o} \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	3.02 ± 0.47 *	2.47 ± 0.39	0.031	1.27	Large
CON $90^{o} \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	1.61 ± 0.20	1.47 ± 0.22	0.143	0.67	Moderate
CON $180^{o} \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	2.32 ± 0.43	2.94 ± 0.32	0.113	1.64	Large
CON $180^{o} \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	1.41 ± 0.22	1.36 ± 0.22	0.617	0.23	Small
ECC $90^{o} \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	3.58 ± 0.84	3.06 ± 0.54	0.117	0.74	Moderate
ECC $90^{o} \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	2.32 ± 0.47	2.02 ± 0.33	0.117	0.74	Moderate
ECC $180^{o} \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	3.15 ± 0.75	2.96 ± 0.54	0.536	0.29	Small
ECC $180^{o} \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	2.34 ± 0.34	2.18 ± 0.34	0.329	0.47	Small

Note: Comparison measured by independent t-test (Significance $p \leq 0.05$). BW = Bodyweight (kg), 1RM = one repetition max, ISO = isometric torque, CON = concentric isokinetic torque, ECC = eccentric isokinetic torque, EXT = knee extensors, FLX = knee flexor. * $p \leq 0.05$, ** $p \leq 0.01$

Table 13. Mean ± SD comparison isokinetic eccentric and concentric torque ratios between non-dominate leg (NDL) faster and slower participants.

ECC : CON ratio	**NDL Faster (n = 10)**	**NDL Slower (n = 10)**	***p***	**g**	***Effect Size magnitude descriptor***
ECC : CON EXT 90°·s^{-1}	1.18 ± 0.21	1.19 ± 0.16	0.917	0.05	Trivial
ECC : CON FLX 90°·s^{-1}	1.46 ± 0.33	1.39 ± 0.27	0.629	0.23	Small
ECC : CON EXT 180°·s^{-1}	1.46 ± 0.25	1.70 ± 0.35	0.382	0.79	Moderate
ECC : CON FLX 180°·s^{-1}	1.70 ± 0.35	1.64 ± 0.34	0.737	0.17	Trivial

Note: Comparison measured by independent t-test (Significance $p \leq 0.05$). ISO = isometric torque, CON = concentric isokinetic torque, ECC = eccentric isokinetic torque, EXT = knee extensors, FLX = knee flexor. * $p \leq 0.05$, ** $p \leq 0.01$

Table 14. Mean ± SD comparison isokinetic eccentric and concentric torque ratios between non-dominate leg (NDL) faster and slower participants.

ECC : ISO ratio	**NDL Faster (n = 10)**	**NDL Slower (n = 10)**	***p***	**g**	***Effect Size magnitude descriptor***
ECC 90°·s^{-1} : ISO EXT	1.00 ± 0.11	1.05 ± 0.20	0.448	0.31	Small
ECC 90°·s^{-1} : ISO FLX	1.20 ± 0.21	1.28 ± 0.29	0.456	0.32	Small
ECC 180°·s^{-1} : ISO EXT	0.88 ± 0.12	1.01 ± 0.16	0.052	0.92	Moderate
ECC 180°·s^{-1} : ISO FLX	1.21 ± 0.14	1.39 ± 0.27	0.076	0.84	Moderate

Note: Comparison measured by independent t-test (Significance $p \leq 0.05$). ISO = isometric torque, CON = concentric isokinetic torque, ECC = eccentric isokinetic torque, EXT = knee extensors, FLX = knee flexor. * $p \leq 0.05$, ** $p \leq 0.01$.

3.2.4.3 Pooled dominant and non-dominant leg muscle function comparisons

No significant differences in muscle function variables were noted between participants during DL and NDL COD as shown in Table 15.

Table 15. Mean ± SD comparison of muscle function variables between pooled dominant leg (DL) and non-dominant leg (NDL) COD.

	DL (n = 20)	**NDL (n = 20)**	***p***	**g**	***Effect Size magnitude descriptor***
Leg press and leg curl 1RM					
Leg press CON 1RM ($kg \cdot BM^{-1}$)	1.20 ± 0.19	1.25 ± 0.33	0.368	0.19	Trivial
Leg press ECC 1RM ($kg \cdot BM^{-1}$)	1.51 ± 0.32	1.74 ± 0.37	0.652	0.66	Moderate
Leg curl CON 1RM ($kg \cdot BM^{-1}$)	0.52 ± 0.20	0.60 ± 0.13	0.101	0.47	Small
Leg curl ECC 1RM ($kg \cdot BM^{-1}$)	0.66 ± 0.26	0.71 ± 0.18	0.836	0.22	Small
Isometric and isokinetic torque					
ISO EXT ($Nm \cdot BM^{-1}$)	1.32 ± 0.42	1.22 ± 0.26	0.946	0.29	Small
ISO FLX ($Nm \cdot BM^{-1}$)	1.60 ± 0.37	1.61 ± 0.34	0.154	0.03	Trivial
CON $90^{o} \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	3.27 ± 0.57	3.28 ± 0.63	0.274	0.02	Trivial
CON $90^{o} \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	1.70 ± 0.26	1.77 ± 0.29	0.477	0.25	Small
CON $180^{o} \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	0.56 ± 0.08	0.57 ± 0.09	0.329	0.12	Trivial
CON $180^{o} \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	0.71 ± 0.13	0.70 ± 0.13	0.207	0.08	Trivial
ECC $90^{o} \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	2.18 ± 0.30	2.19 ± 0.39	0.383	0.03	Trivial
ECC $90^{o} \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	1.29 ± 0.17	1.36 ± 0.22	0.699	0.36	Moderate
ECC $180^{o} \cdot s^{-1}$ EXT ($Nm \cdot BM^{-1}$)	2.75 ± 0.38	2.81 ± 0.47	0.178	0.14	Trivial
ECC $180^{o} \cdot s^{-1}$ FLX ($Nm \cdot BM^{-1}$)	1.50 ± 0.18	1.52 ± 0.21	0.832	0.10	Trivial

Note: Comparison measured by paired sample t-test (Significance $p \leq 0.05$). DL = Dominant leg, NDL =Non-dominant leg, BM = Bodymass (kg), ISO = isometric torque, CON = concentric isokinetic torque, ECC = eccentric isokinetic torque, EXT = knee extensors, FLX = knee flexor. * $p \leq 0.05$, ** $p \leq 0.01$

3.3 Correlations to COD performance

3.3.1 Ground reaction force correlations

3.3.1.1 Dominant leg ground reaction force correlations

The correlations between DL 1-1m COD time and GRF during the last three steps are illustrated in Figure 6. no significant correlations between 1-1 m COD time and GRF of the last three steps were found (DL plant propulsive impulse, r (95% CI) = 0.031 (-0.438 - 0.171), *p* = 0.890; DL plant braking impulse, r (95% CI) = -0.422 (-0.195 – 0.610), *p* = 0.051; DL PEN braking impulse, r (95% CI) = 0.419 (-0.018 – 0.210), *p* = 0.052; and DL PEN-1 braking impulse, r (95% CI) = -0.192 (-0.106 – 0.713), *p* = 0.393).

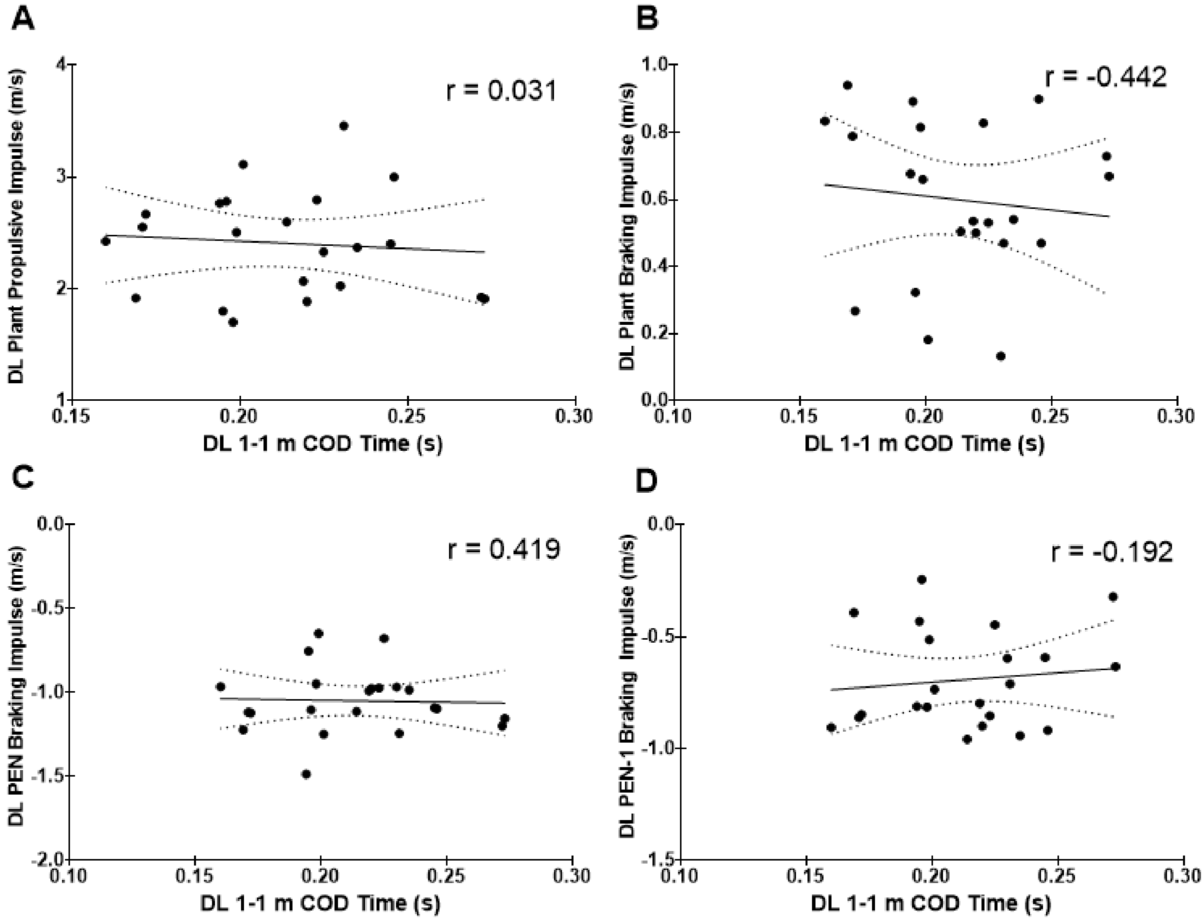

Figure 6. Scatter plot with 95% confidence interval band of dominant leg (DL) ground reaction force variables to 1-1 m COD time.
Note: The figures shown are (A) plant propulsive impulse, (B) plant braking impulse, (C) penultimate (PEN) braking impulse, (D) one step prior to penultimate (PEN-1) braking impulse. Linear regression line for each plot is shown but none of correlations are significant with 1-1m COD time.

3.3.1.2 Non-dominant leg ground reaction force correlations

The correlations between NDL 1-1 m COD time and GRF during the last three steps are illustrated in Figure 7. No significant correlations between 1-1 m COD time and GRF of the last three steps were evident (NDL plant propulsive impulse, r (95% CI) = 0.143 (-0.187 – 0.472, p = 0.513; NDL plant braking impulse, r (95% CI) = 0.124 (-0.234 – 0.448), p = 0.507; NDL PEN braking impulse, r (95% CI) = 0.208 (-0.331 – 0.692), p = 0.353; and NDL PEN-1 braking impulse, r (95% CI) = -0.013 (-0.394 – 0.370), p = 0.955).

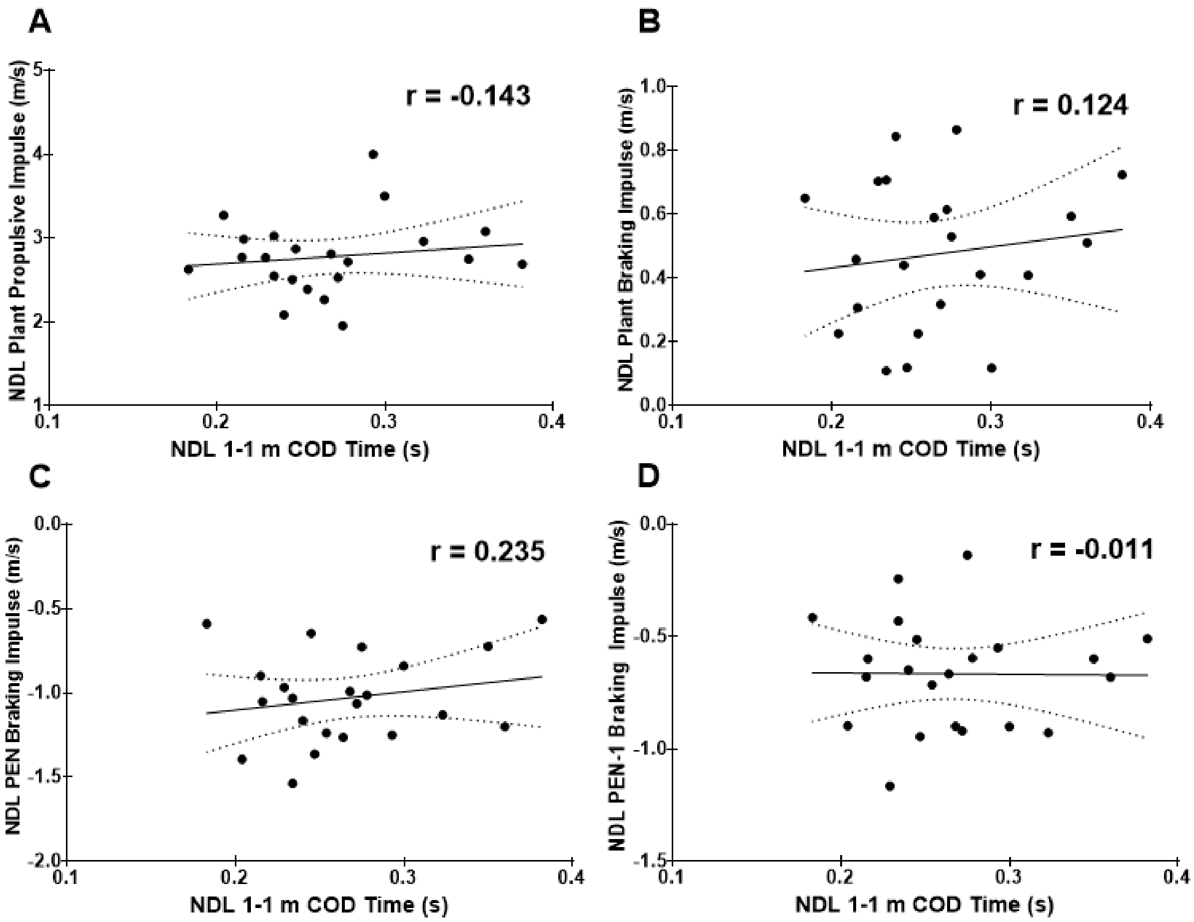

Figure 7. Scatter plot with 95% confidence interval band of non-dominant leg (NDL) ground reaction force variables to 1-1 m COD time.
Note: The figures shown are (A) plant propulsive impulse, (B) plant braking impulse, (C) penultimate (PEN) braking impulse, (D) Step prior to penultimate (PEN-1) braking impulse. Linear regression line for each plot is shown but none of the correlations are significant with 1-1m COD time.

3.3.2 Correlations between 1-1 m COD time and muscle function measures

3.3.2.1 Dominant leg press and leg curl

The correlations between DL 1-1m COD time and DL leg press as well as leg curl 1RM (concentric and eccentric) are illustrated in Figure 6. No significant correlations were observed with DL leg press eccentric 1RM and DL leg curl 1RM (concentric and eccentric) (DL leg press concentric 1RM (r (95% CI) = 0.449 (0.023 – 0.828), *p* = 0.076); DL leg press eccentric 1RM, r (95% CI) = 0.351 (-0.289 – 0.728), *p* = 0.129; DL leg curl concentric 1RM, r (95% CI) = 0.102 (-0.547 – 0.320), *p* = 0.696; and DL leg curl eccentric 1RM, r (95% CI) = -0.030 (-0.635 – 0.097), *p* = 0.899).

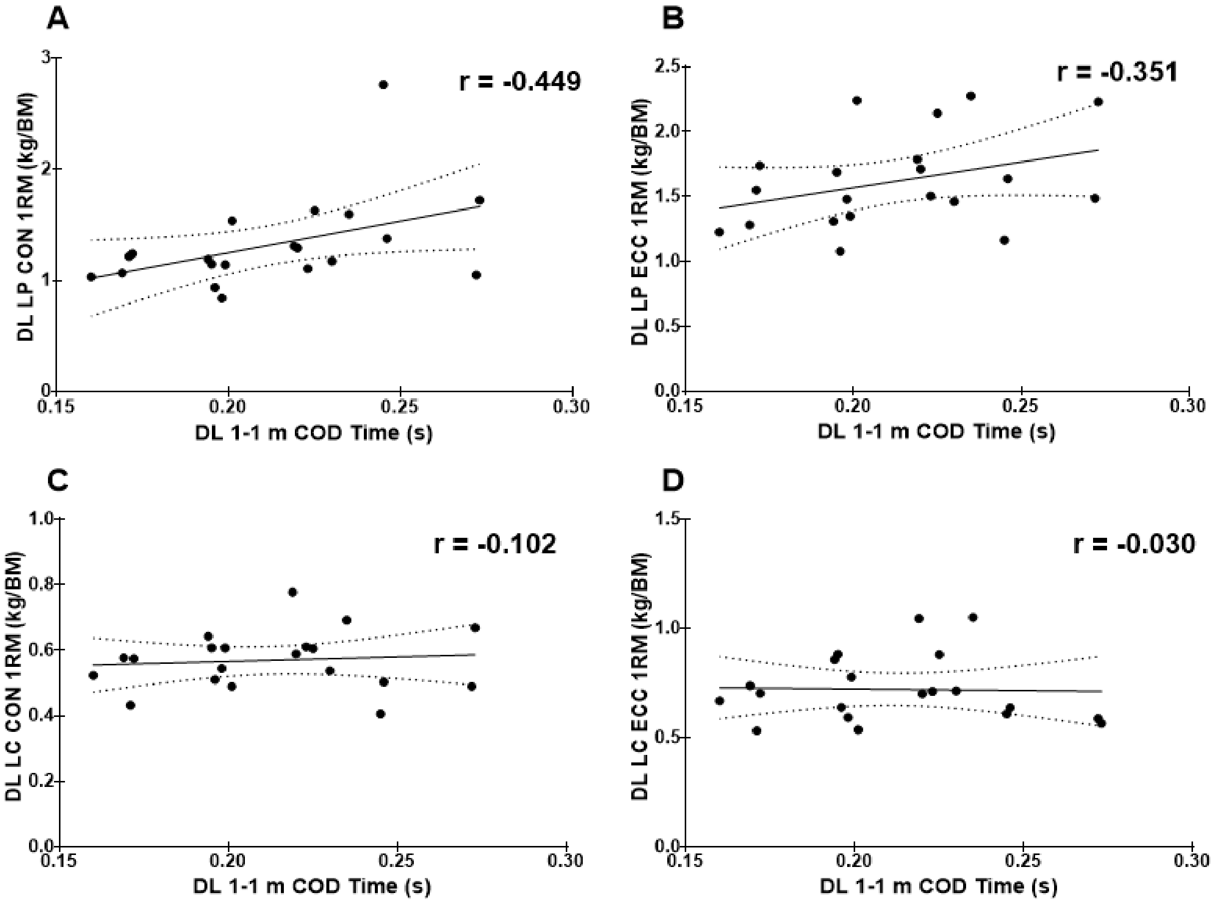

Figure 8. Scatter plot with 95% confidence interval band of dominant leg (DL) 1-1 m COD time to leg press (LP) and leg curl (LC) one-repetition max (1RM).
Note: The figures shown are (A) DL LP concentric (CON) 1RM, (B) DL LP eccentric (ECC) 1RM, (C) DL LC CON 1RM, and (D) DL LC ECC 1RM. Linear regression line for each plot is shown but none of the correlations are significant with 1-1m COD time.

3.3.2.2 Dominant leg isometric peak torque

The correlations between DL 1-1 m COD time and DL isometric peak torque of the knee extensors and knee flexors are illustrated in Figure 8. No significant correlations between DL 1-1 m COD time and DL isometric peak torque were found (DL isometric knee extensors peak torque, r (95% CI) = -0.202 (-0.605 – 0.136), p = 0.393; and DL isometric knee flexor peak torque, r (95% CI) = -0.408 (-0.764 – 0.043), p = 0.075).

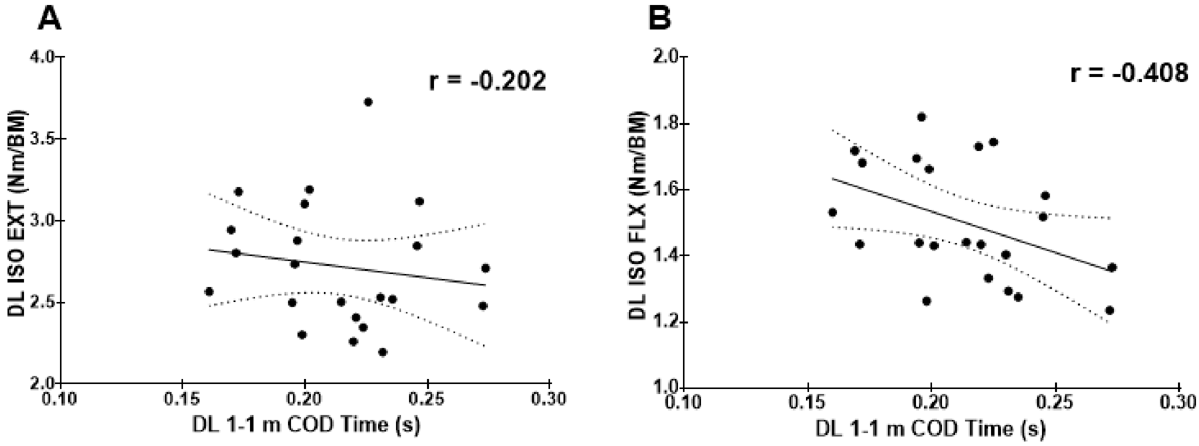

Figure 9. Scatter plot with 95% confidence interval band of dominant leg (DL) isometric peak torque to 1-1 m COD time.
Note: The figures shown are (A) DL isometric (ISO) knee extensor (EXT) peak torque, (B) DL ISO knee flexor (FLX) peak torque. Linear regression line for each plot is shown but none of the correlations are significant with 1-1m COD time.

3.3.2.3 Dominant leg isokinetic peak torque

The correlations between DL 1-1 m COD time and DL concentric isokinetic ($90^{o}{\cdot}s^{-1}$ and $180^{o}{\cdot}s^{-1}$) peak torque of the knee extensors and knee flexors are illustrated in Figure 10. No significant correlations between DL 1-1 m COD time and DL isometric concentric peak torque were found after Holm-Bonferroni correction for multiple comparisons. The results with corrected alpha levels are as follows; DL concentric isokinetic $90^{o}{\cdot}s^{-1}$ knee extensors peak torque, r (95% CI) = -0.125 (-0.496 – 0.208), p = 0.483; DL concentric isokinetic $90^{o}s^{-1}$ knee flexor peak torque, r (95% CI) = -0.420 (-0.686 - -0.061), p = 0.074; DL concentric isokinetic $180^{o}{\cdot}s^{-1}$ knee extensors peak torque, r (95% CI) = -0.134 (-0.515 – 0.179), p = 0.455; and DL concentric isokinetic $180^{o}{\cdot}s^{-1}$ knee flexor peak torque, r (95% CI) =-0.489 (-0.734 - -0.105), p = 0.086.

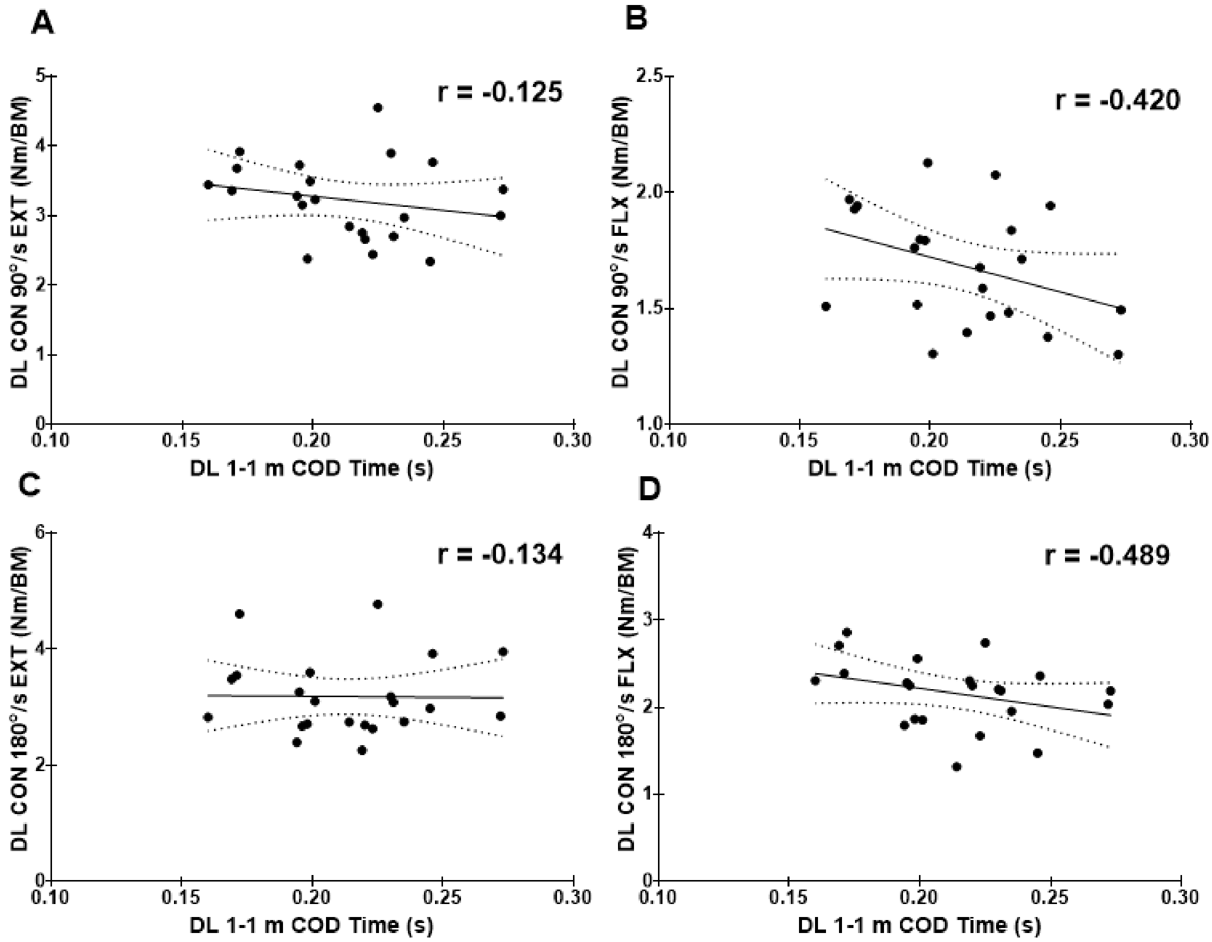

Figure 10. Scatter plot with 95% confidence interval band of dominant leg (DL) isokinetic measurements to 1-1 m COD time.

Note: The figures shown are (A) body mass (kg) normalised DL concentric isokinetic (CON) $90^o \cdot s^{-1}$ knee extensor (EXT) peak torque, (B) body mass normalised DL CON 90°·s-1 knee flexor (FLX) torque, (C) body mass normalised DL CON $180^o \cdot s^{-1}$ EXT torque, (D) body mass normalised DL CON $180^o \cdot s^{-1}$ FLX torque. Linear regression line for each plot is shown but none of the correlations are significant with 1-1m COD time.

The correlations between DL 1-1 m COD time and DL eccentric isokinetic ($90^o \cdot s^{-1}$ and $180^o \cdot s^{-1}$) peak torque of the knee extensors and knee flexors are illustrated in Figure 11. No significant correlations between DL 1-1 m COD time and DL eccentric isometric peak torque were noted after Holm-Bonferroni correction for multiple comparisons. The results with corrected alpha levels are as follows; DL eccentric isokinetic $90^o \cdot s^{-1}$ knee extensors peak torque, r (95% CI) = -0.009 (-0.502 – 0.413), p = 0.949; DL eccentric isokinetic $90^o \cdot s^{-1}$ knee flexor peak torque, r (95% CI) = -0.379 (-0.664 - -0.037), p = 0.129; DL eccentric isokinetic $180^o \cdot s^{-1}$ knee extensors peak torque, r (95% CI) = -0.114 (-0.649 – 0.223), p = 0.614; and DL eccentric isokinetic $180^o \cdot s^{-1}$ knee flexor peak torque, r (95% CI) = -0.481 (-0.744 - -0.164), p = 0.086.

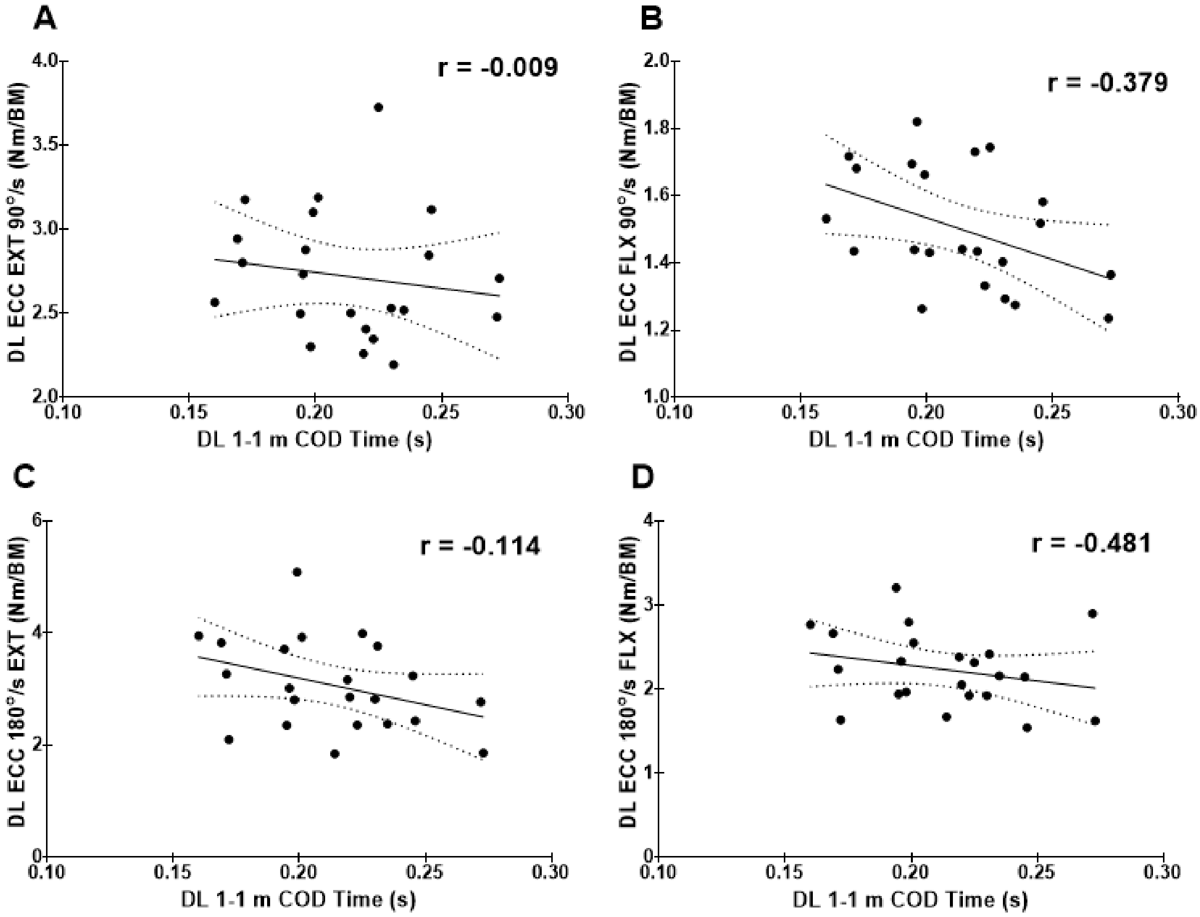

Figure 11. Scatter plot with 95% confidence interval band of dominant leg (DL) isokinetic measurements to 1-1 m COD time.

Note: The figures shown are (A) body mass (kg) normalised DL eccentric isokinetic (ECC) $90^{o}\cdot s^{-1}$ knee extensor (EXT) peak torque, (B) body mass normalised DL ECC 90^{o}·s-1 knee flexor (FLX) torque, (C) body mass normalised DL ECC $180^{o}\cdot s^{-1}$ EXT torque, (D) body mass normalised DL ECC $180^{o}\cdot s^{-1}$ FLX torque. Linear regression line for each plot is shown but none of the correlations are significant with 1-1m COD time.

3.3.2.4 Dominant leg COD and drop jump RSI

The correlations between DL 1-1 m COD time and DJ RSI are illustrated in Figure 12. No significant correlations between DL 1-1 m COD time and DJ RSI at all three heights were found (20 cm DJ RSI, r (95% CI) = 0.128 (-0.309 – 0.537), $p = 0.725$; 40 cm DJ RSI, r (95% CI) = 0.139 (-0.394 – 0.606), $p = 0.813$; and 60 cm DJ RSI, r (95% CI) = 0.019 (-0.503 – 0.509), $p = 0.896$).

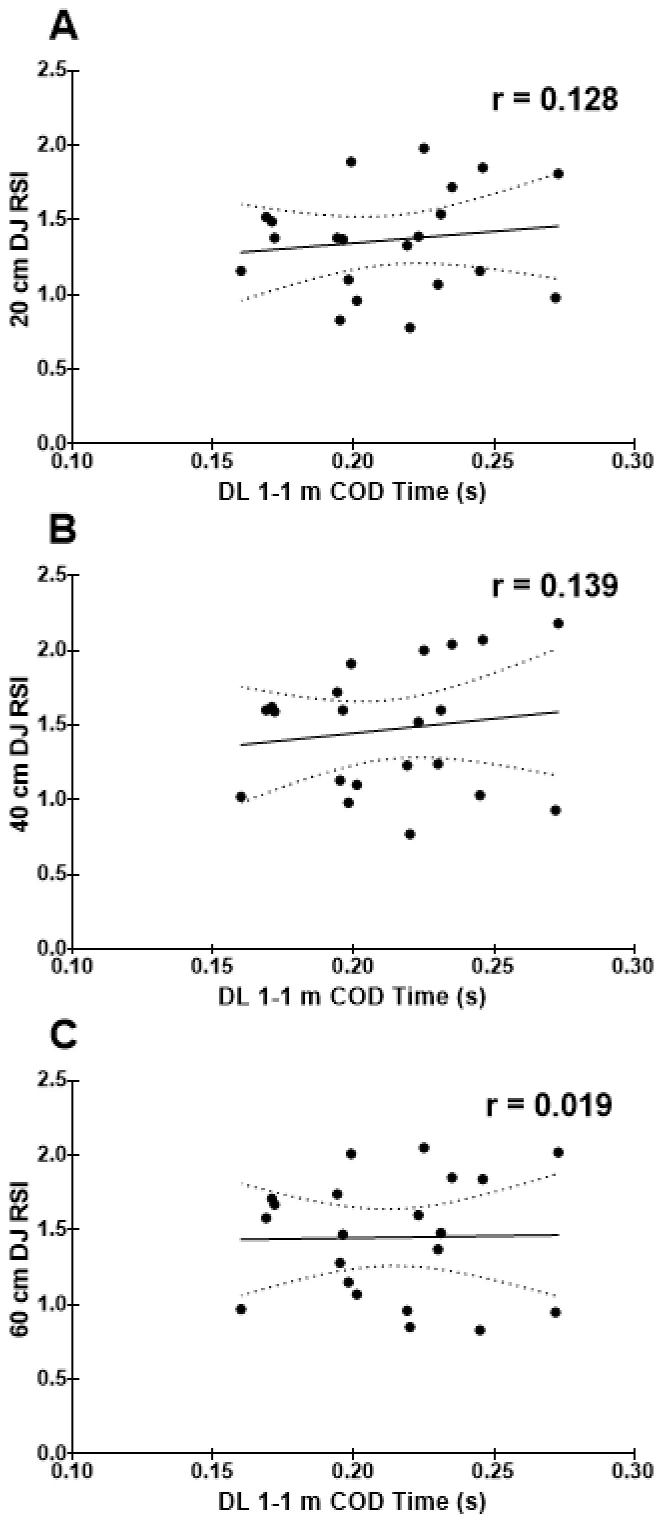

Figure 12 . Scatter plot with 95% confidence interval band of drop jump (DJ) reactive strength index (RSI) measurements to dominant leg (DL) 1-1 m COD time.

Note: The figures shown are (A) 20 cm DJ RSI, (B) 40 cm DJ RSI, (C) 60 cm DJ RSI. Linear regression line for each plot is shown but none of the correlations are significant with 1-1m COD time.

3.3.2.5 Non-dominant leg press and leg curl

The correlations between NDL 1-1m COD time and NDL leg press and leg curl 1RM (concentric and eccentric) are illustrated in Figure 13. No significant correlations were observed between NDL 1-1m COD time and NDL leg press as well as leg curl 1RM (concentric and eccentric) (NDL leg press concentric 1RM, r (95% CI) = 0.047 (-0.378 – 0.523), *p* = 0.845; NDL leg press eccentric 1RM, r (95% CI) = 0.202 (-0.243 – 0.630), *p* = 0.392; NDL leg curl concentric 1RM, r (95% CI) = 0.018 (-0.660 – 0.548), *p* = 0.430; and NDL leg curl eccentric 1RM, r (95% CI) = -0.052 (-0.598 – 0.518), *p* = 0.829).

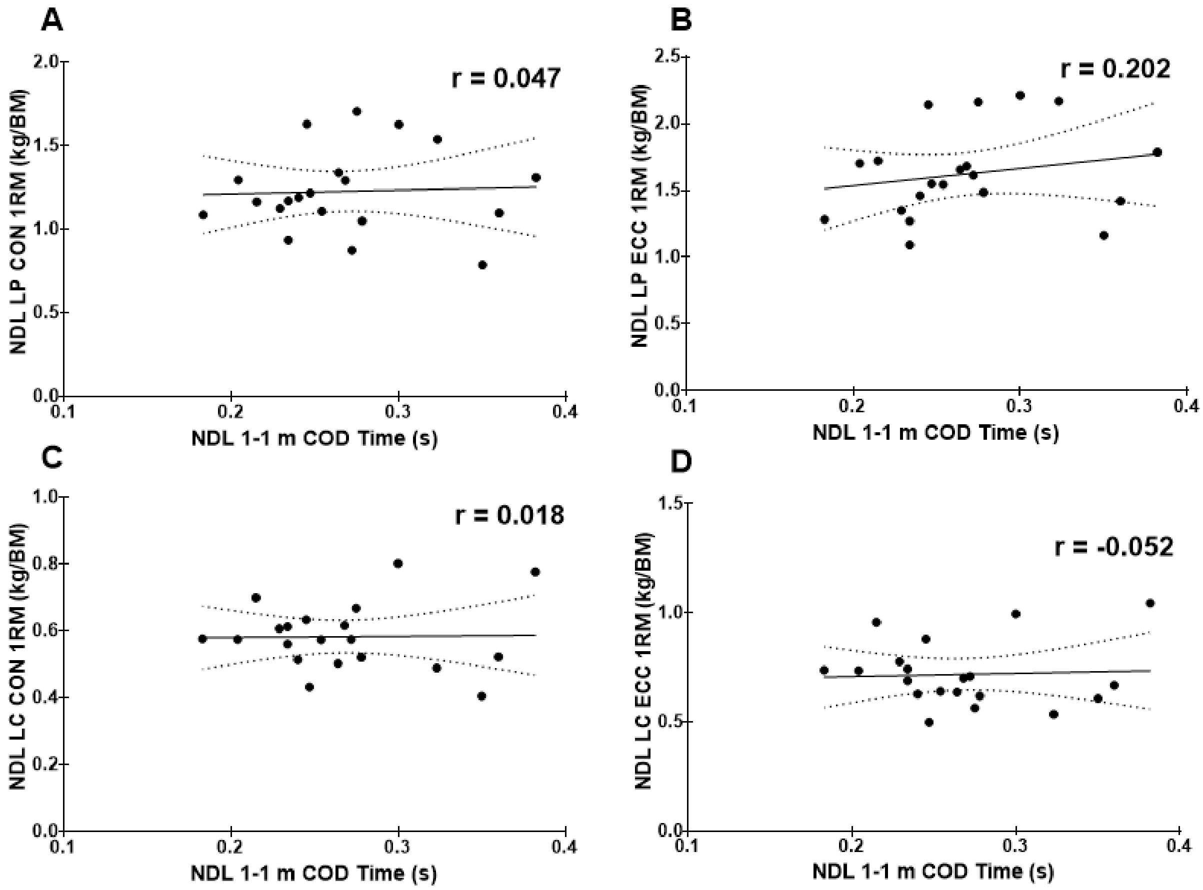

Figure 13. Scatter plot with 95% confidence interval band of non-dominant leg (NDL) 1-1 m COD time to leg press (LP) and leg curl (LC) one-repetition max (1RM).
Note: The figures shown are (A) NDL LP concentric (CON) 1RM, (B) NDL LP eccentric (ECC) 1RM, (C) NDL LC CON 1RM, and (D) NDL LC ECC 1RM. Linear regression line for each plot is shown but none of the correlations are significant with 1-1m COD time.

3.3.2.6 Non-dominant leg isometric peak torque

The correlations between NDL 1-1 m COD time and NDL isometric peak torque of the knee extensors and knee flexors are illustrated in Figure 14. Moderate significant correlation was found between NDL 1-1 m COD time and NDL isometric knee flexor peak torque after sequential Bonferroni correction (r (95% CI) = -0.473 (-0.794 - -0.109), *p* = 0.048). However, no significant correlation was observed NDL isometric peak torque were noted (r (95% CI) = -0.413 (-0.700 - -0.065), *p* = 0.062).

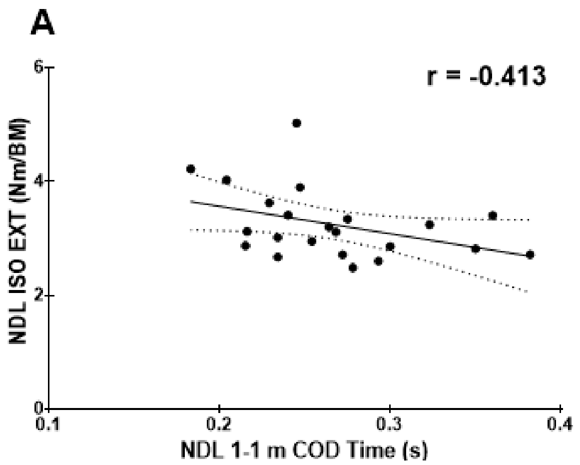

Figure 14. Scatter plot with 95% confidence interval band of non-dominant leg (NDL) isometric (ISO) peak torque to 1-1 m COD time.
*Note: The figures shown are (A) NDL ISO knee extensor (EXT) peak torque, (B) NDL ISO knee flexor (FLX) peak torque. * $p \leq 0.05$, ** $p \leq 0.01$*

3.3.2.7 Non-dominant leg isokinetic peak torque

The correlations between NDL 1-1 m COD time and NDL concentric isokinetic (90°·s^{-1} and 180°·s^{-1}) peak torque of the knee extensors and knee flexors are illustrated in Figure 15. No significant correlations between NDL 1-1 m COD time and NDL isometric concentric peak torque were noted after sequential Bonferroni correction for multiple comparisons. The results with corrected alpha levels are as follows; NDL concentric isokinetic 90°·s^{-1} knee extensors peak torque (r (95% CI) = -0.388 (-0.731 - -0.004), *p* = 0.174); NDL concentric isokinetic 90°·s^{-1} knee flexor peak torque (r (95% CI) = -0.388 (-0.685 – 0.156), *p* = 0.174); DL concentric isokinetic 180°·s^{-1} knee extensors peak torque (r (95% CI) = -0.364 (-0.708 – 0.061), *p* = 0.084);

and DL concentric isokinetic $180^{o}\cdot s^{-1}$ knee flexor peak torque (r (95% CI) = 0.011 (-0.389 – 0.394), p = 0.905).

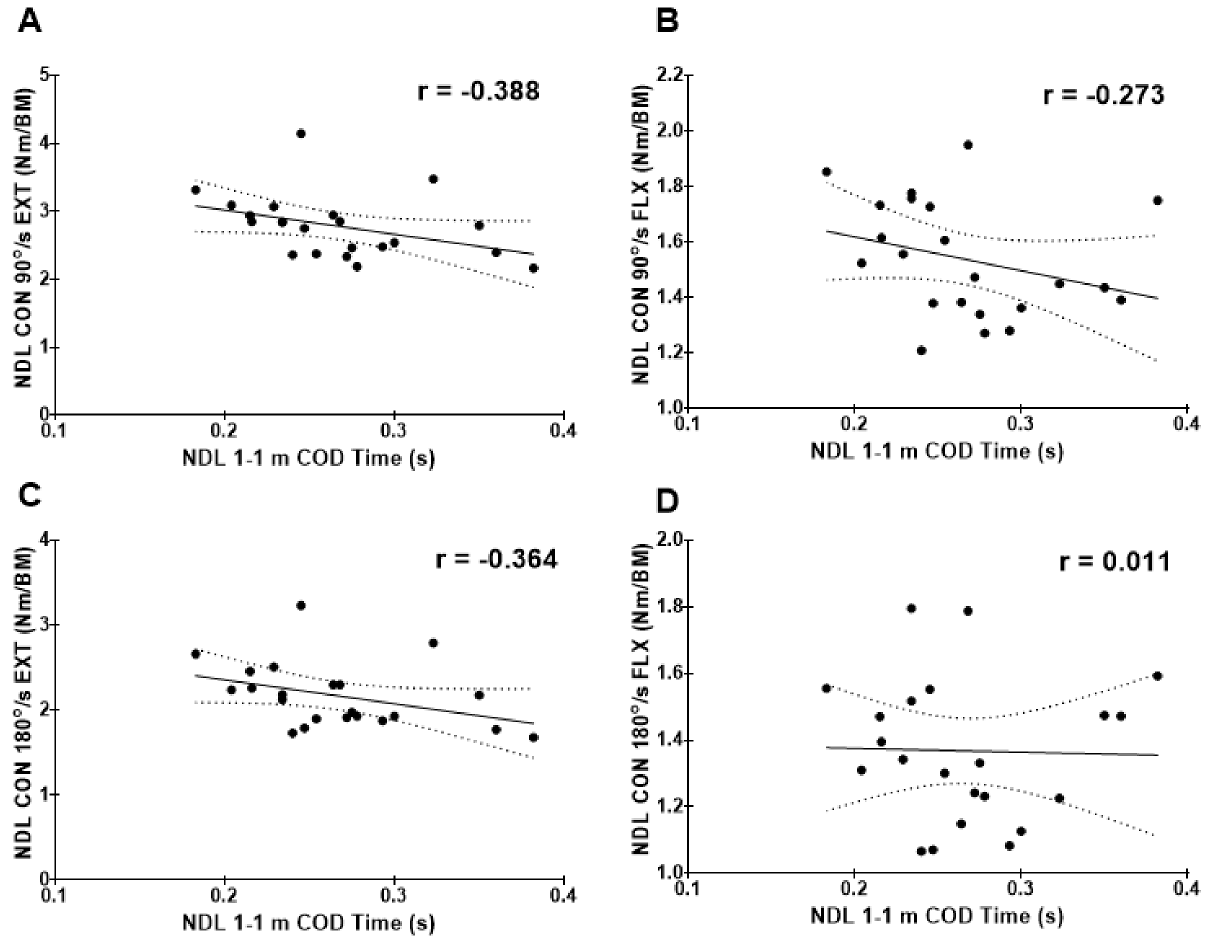

Figure 15. Scatter plot with 95% confidence interval band of non-dominate leg (NDL) isokinetic measurements to 1-1 m COD time.
Note: The figures shown are (A) body mass (kg) normalised DL concentric isokinetic (CON) $90^{o}\cdot s^{-1}$ knee extensor (EXT) peak torque, (B) body mass normalised DL CON $90^{o}\cdot s^{-1}$ knee flexor (FLX) torque, (C) body mass normalised DL CON $180^{\cdot o}s^{-1}$ EXT torque, (D) body mass normalised DL CON $180^{o}\cdot s^{-1}$ FLX torque. Linear regression line for each plot is shown but none of the correlations are significant with 1-1m COD time.

The correlations between NDL 1-1 m COD time and DL eccentric isokinetic ($90^{o}\cdot s^{-1}$ and $180^{o}\cdot s^{-1}$) peak torque of the knee extensors and knee flexors are illustrated in Figure 16. Moderate to large significant correlations were found between NDL 1-1 m COD time and NDL eccentric isokinetic $90^{o}\cdot s^{-1}$ knee extensor peak torque and NDL eccentric isokinetic $90^{o}\cdot s^{-1}$ knee flexor peak torque after sequential Bonferroni correction. The results with corrected alpha levels are as follows; NDL eccentric isokinetic $90^{o}\cdot s^{-1}$ knee extensors peak torque (r (95% CI) = -0.470 (-0.772 – 0.002), p = 0.05); and DL eccentric isokinetic $90^{o}\cdot s^{-1}$ knee flexor peak torque (r (95% CI) = -0.648 (-0.903 - -0.260), p = 0.012). However, no significant correlations were noted for NDL eccentric isokinetic $180^{o}\cdot s^{-1}$ knee extensors peak torque (r (95% CI) = -0.270 (-0.594 – 0.131), p = 0.359), and NDL eccentric isokinetic $180^{o}\cdot s^{-1}$ knee flexor peak torque (r (95% CI) = -0.290 (-0.678 – 0.172), p = 0.221).

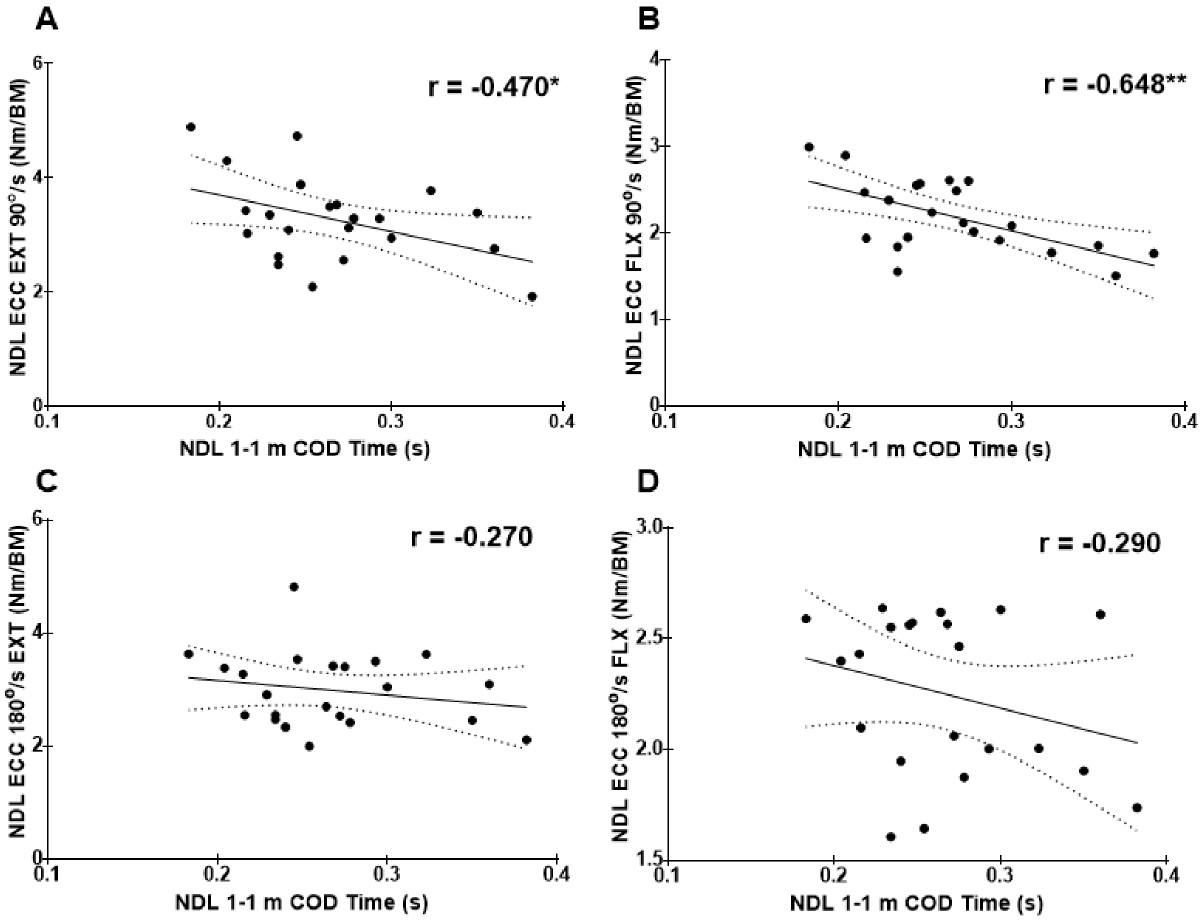

Figure 16. Scatter plots with 95% confidence interval band of non-dominant leg (NDL) eccentric (ECC) isokinetic measurements to 1-1 m COD time.
*Note: The figures shown are (A) body mass (kg) normalised NDL ECC concentric isokinetic (CON) $90^{o}\cdot s^{-1}$ knee extensor (EXT) peak torque, (B) body mass normalised NDL ECC CON $90^{o}\cdot s^{-1}$ knee flexor (FLX) torque, (C) body mass normalised NDL ECC CON $180^{o}\cdot s^{-1}$ EXT torque, (D) body mass normalised NDL ECC CON $180^{o}\cdot s^{-1}$ FLX torque. * $p \leq 0.05$, ** $p \leq 0.01$*

3.3.2.8 Non-dominant leg COD time and drop jump reactive strength index

The correlations between NDL 1-1 m COD time and DJ RSI are illustrated in Figure 17. Large significant correlation was found between NDL 1-1 m COD time and 60 cm DJ RSI after sequential Bonferroni correction (r (95% CI) = -0.556 (-0.778 – -0.198), p = 0.048). However, no significant correlations were noted with 20 cm DJ RSI (r (95% CI) = --0.196 (-0.491 – 0.120), p = 0.644), and 40 cm DJ RSI (r (95% CI) = -0.352 (-0.636 - -0.002), p = 0.146).

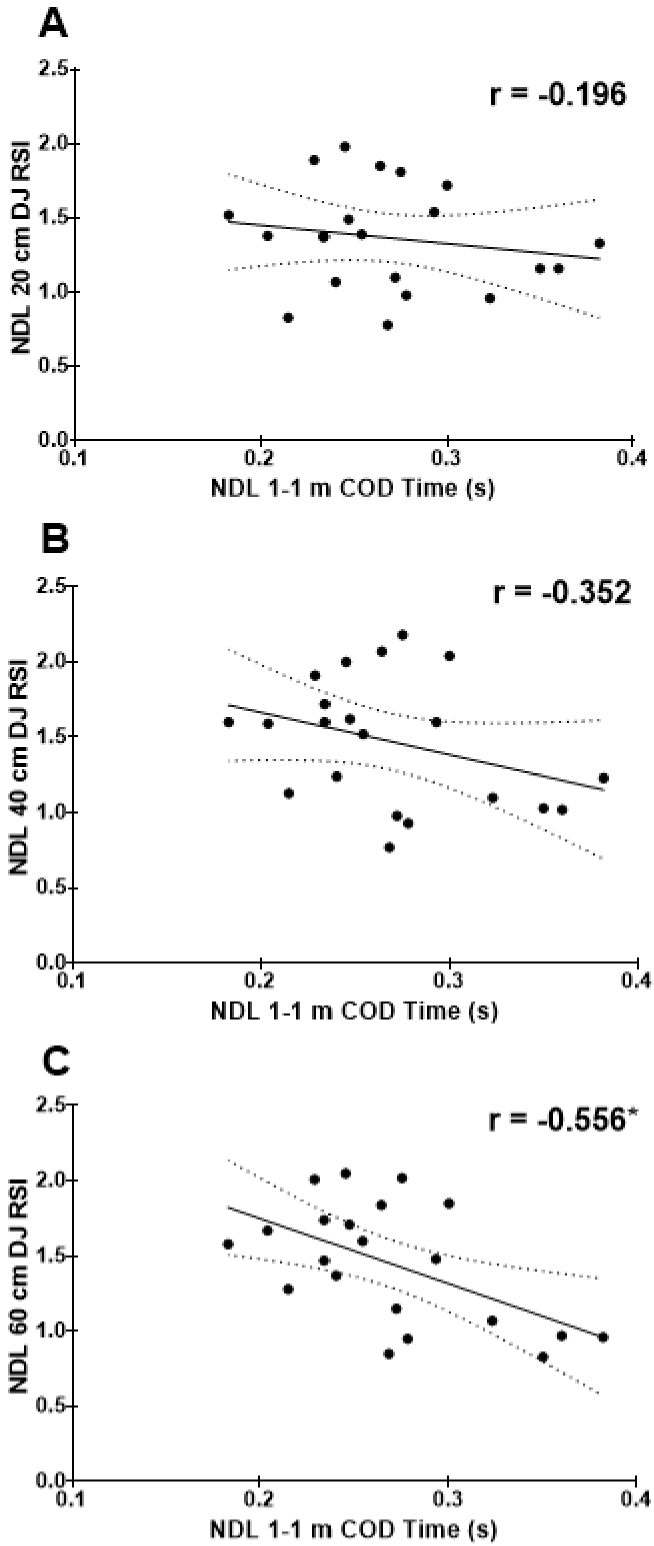

Figure 17. Scatter plots with 95% confidence interval band of drop jump (DJ) reactive strength index (RSI) measurements to non-dominant leg (NDL) 1-1 m COD time.

Note: The figures shown are (A) 20 cm DJ RSI, (B) 40 cm DJ RSI, (C) 60 cm DJ RSI. Linear regression line for each plot is shown. * $p \leq 0.05$, ** $p \leq 0.01$

Among all the variables measured, only NDL knee extensor and knee flexor $90^{o}\cdot s^{-1}$ isokinetic torque, 60-cm drop jump RSI, and NDL isometric knee flexor torque were found to have moderate to large significant associations with NDL 1-1 m COD. These correlations are illustrated in Figure 18. NDL 1-1 m COD were significantly associated to NDL eccentric knee flexor torque at $90^{o}\cdot s^{-1}$ (r (95% CI) = 0.648 (-0.903 - -0.260), *p* = 0.012), 60-cm drop jump RSI (r (95% CI) = -0.556 (-0.778 – -0.198), *p* = 0.045), NDL flexor torque (r (95% CI) = 0.473 (-0.794 - -0.109), *p* = 0.048) and NDL eccentric knee extensor torque at $90^{o}s^{-1}$ (r (95% CI) = -0.470 (-0.772 – 0.002), *p* = 0.05).

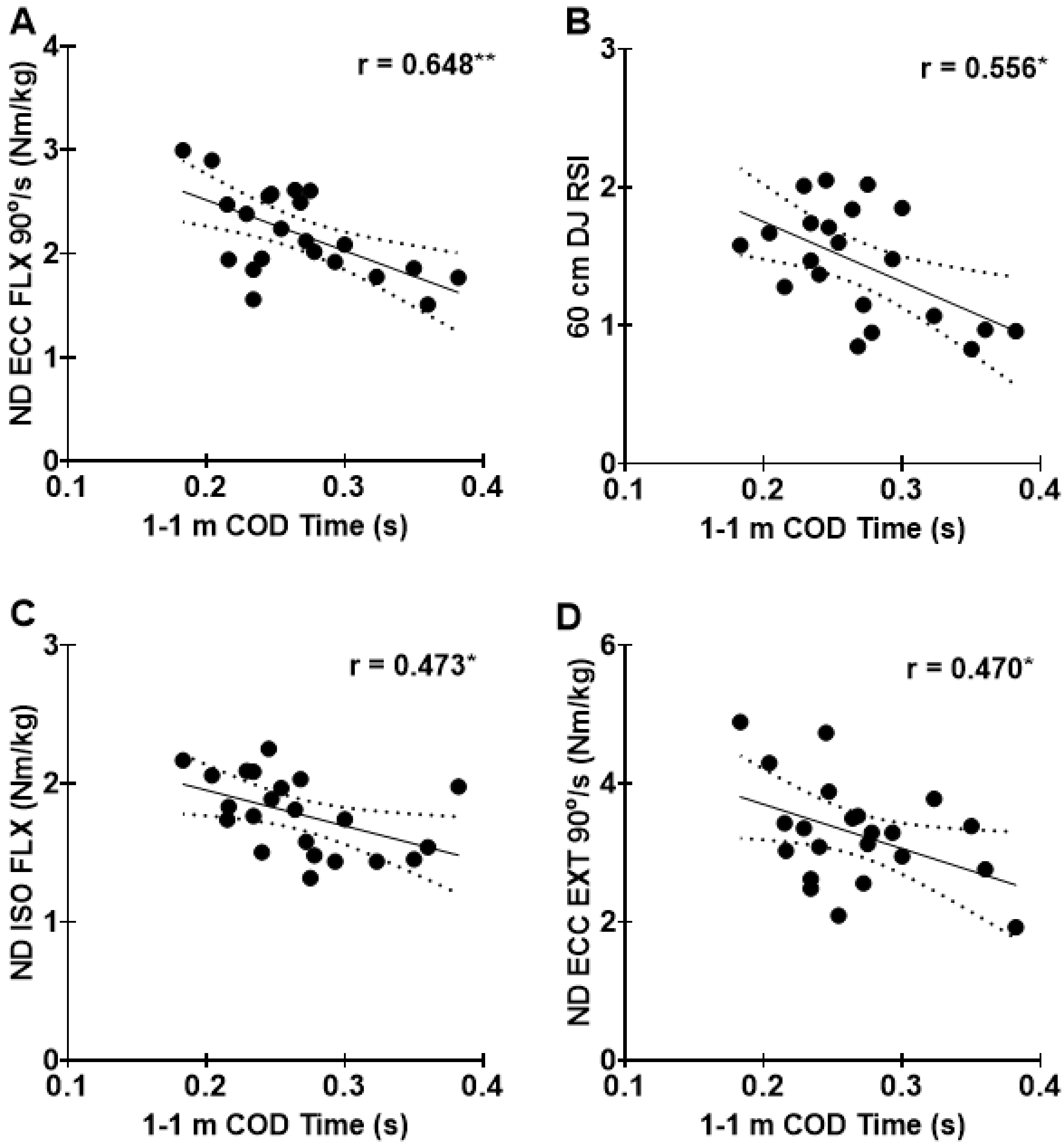

Figure 18. Scatter plots with 95% confidence interval band illustrating the relationship between 1-1 m COD time with (A) non-dominant leg (NDL) isokinetic eccentric (ECC) knee flexor (FLX) torque at 90 $^{\cdot o}s^{-1}$; (B) 60 cm drop jump (DJ) reactive strength index (RSI); (C) NDL isometric (ISO) FLX torque and (D) NDL ECC knee extensor (EXT) torque at 90 $^{\cdot o}s^{-1}$.
*$p \leq 0.05$, ** $p \leq 0.01$*

Chapter 4. DISCUSSION

The aim of this study was to investigate the deceleration kinetics of 90^{o} COD performance in relation to the last three steps (plant, PEN and PEN-1) by comparing faster and slower performance based on the 1-1 m COD time. In addition, this study examined the relationships between the deceleration kinetics and several muscle function measures. The results revealed that the 1-1 m COD time was reliable and was able to distinguish between faster and slower COD performance. There were no significant GRF differences between faster and slower performers for DL and NDL COD when comparing individual braking steps. However, faster DL COD performers applied significantly greater PEN braking impulse relative to the PEN-1. Muscle function comparison showed that the faster NDL COD had significantly greater NDL isometric knee extensor and flexor strength, and concentric isokinetic 90$^{o}\cdot s^{-1}$ but not 180$^{o}\cdot s^{-1}$ knee extensor strength. Additionally, no significant difference in muscle function was observed between faster and slower DL COD. When comparing the DL and NDL COD kinetics for all participants together, significantly lower propulsive impulse and higher braking impulse during the plant step were observed for the DL than NDL, but individual data showed little separation in the both propulsive and plant braking impulse between DL and NDL. Lastly, no significant associations were found between 1-1 m COD time and any dependent variables for DL COD performance, but isokinetic 90$^{o}\cdot s^{-1}$ eccentric knee flexor and extensor torque, 60 cm DJ RSI and NDL isometric knee flexor torque were found to be significantly related to the 1-1 m COD time for NDL. These results suggest that braking GRF at each deceleration step may not be the differentiating factor for faster and slower COD performance in recreational level athlete, furthermore a participant's individual braking strategy may have a larger contribution to COD performance. The lack of significant differences and correlations between COD performance, GRF and muscle function variables further supports the explanation that technique or braking strategies may be a larger contributing factor for COD performance in recreational athletes.

4.1 Reliability of 1-1 m COD time

To the author's knowledge this was the first study to examine COD performance based on 1-1 m COD time. Previous studies have examined COD performance based on the total time taken to complete the whole COD task (Dos'Santos et al., 2016; Gabbett et al., 2008; Jones et al., 2017; Spiteri et al., 2015a; Young et al., 2002), which is likely to be confounded by other physical abilities such as linear sprint ability (Brughelli et al., 2008; Nimphius et al., 2017). The 1-1 m COD time was first measured using a 3D motion capture system. Sayers (2015) demonstrated that 1-1 m COD time was a reliable COD test characterised by low CV% and high ICC values between sessions (CV% = 2.4%, ICC = 0.82) in elite rugby players. Similarly, the present study found that between-session reliability for both DL and NDL 1-1 COD time had low CV% and very high ICC values (CV% = 7.7 - 9.3 %, ICC = 0.769 – 0.850) (Table 1). There were significant differences in between-session NDL measures for 1-1 m COD and total time (Table 1), which may be due to learning effect. Additionally, due to the multisport background used in this study, variability might have been larger among the participants in this study than the single sport athletes used by previous study (Sayers, 2015). As this was the first study to examine the 1-1 m COD time using timing gates, comparisons of between-session differences with other studies are unavailable. The significant difference in between-session 1-1 m COD time should be considered when examining the kinetics and muscle function of faster and slower COD discussed below.

4.2 Ground reaction force of the last three steps during 1-1 m COD

Recent studies have examined the role of the PEN step during COD performance and showed that greater horizontal braking force and shorter contact time resulted in faster COD performance (Dos'Santos et al., 2016; Jones et al., 2017). Thus, it was hypothesised in the present study that faster COD participants would apply higher PEN braking impulse. However, there were no significant differences in braking kinetics among the last three braking steps between faster and slower groups during DL and NDL COD (Table 5 & 6), and pooled DL and NDL COD comparison (Table 7). This may be attributed to the 90^{o} COD test angle used for the current study compared with the 180^{o} COD used by previous researchers (Dos'Santos et al., 2016; Jones et al., 2017). During 180^{o} COD, PEN step is a key step to reach a manageable load for lateral transfer of momentum at the plant step (Dos'Santos et al., 2016; Jones et al., 2017). However, during 90^{o} COD the PEN step may not be a key braking step for faster performance as braking load could have been distributed across the last three steps of the COD rather than focusing on a single step like the PEN step during 180^{o} COD. This explanation is supported by the lack of significant differences and the similarity of braking impulse values among between faster and slower groups during DL and NDL COD as well as pooled DL and NDL COD comparisons seen in Figures 2, 3 and 4.

A novel aspect of this study was to examine the kinetics of the last three steps (plant, PEN and PEN-1) during COD performance. Although there were no significant differences in braking impulse at each step among faster and slower participants, there was significant difference in the change in braking impulse from the PEN-1 to PEN braking step between faster and slower DL COD performance (Table 8, Figure 5). The greater braking impulse from PEN-1 to PEN step in faster DL COD performance, in contrast to the fairly similar braking impulse between PEN-1 and PEN step in slower DL COD participants suggests that braking strategies that applies greater braking at the PEN step may play a role in faster COD performance.

Previous studies have examined braking strategy using the ratio of peak braking force of the PEN step and plant step, and found a higher braking ratio (greater braking at PEN relative to plant step) resulted in faster COD performance (Dos'Santos et al., 2016; Jones et al., 2017). However, the current study did not observe any significant differences in the change in braking impulse between the PEN and plant step among faster and slower participants, which could be due to the different braking load during 90^{o} COD. Furthermore, there was no significant difference in the change in braking impulse from PEN-1 to PEN step among faster NDL COD participants, which indicates faster NDL COD was due to other factors such as lower body position and stiffer trunk during the plant phase or stride frequency before and after the COD (Hewit et al., 2013; Marshall et al., 2014; Sasaki et al., 2011). Nevertheless, the significant difference in the PEN-1 to PEN braking impulse during faster DL COD highlights the importance of examining PEN-1 braking as well as braking strategies used during COD performance in addition to individual step analyses.

It is worth noting that the use of a mobile inertia measurement units such as XSENS to quantify whole body kinematics is fairly new and have the potential to provide coaches with kinematic and kinetic data for player monitoring and detect individual weaknesses during training or when returning from injury. Although no significant difference was observed in the entry and exit velocity of faster and slower participants, braking strategies can also be obtained by the ratio or difference in velocity between braking and propulsive steps (Jones et al. 2017). As systems such as XSENS is mobile, coaches can effectively obtain kinematic and joint kinetic data in a practical setting. However, further studies are required to determine the validity and reliability of such measures outside of a laboratory setting.

Faster COD performers may be better at estimating how much load they can tolerate at the plant step to push off effectively and correctly plan their deceleration. Early braking will reduce braking demands at the plant step and allow more time for propulsive force production leading to faster acceleration after the plant step, thus resulting in faster COD performance (Spiteri et al., 2013; Spiteri et al., 2015a). It is possible, therefore, that faster DL COD performers reached a manageable load at the plant step for re-direction and acceleration by decelerating from the PEN-1 to PEN step instead of focusing braking at the PEN step. This finding suggests that it is advantageous to prioritise braking during COD performance is in line with previous studies suggesting (Dos'Santos et al., 2016; Jones et al., 2017; Spiteri et al., 2013). The results from this study shows the need to examine at least two steps prior to the plant step to account for the deceleration process, as braking strategies leading to faster performance can occur before the PEN step.

The mechanics of the plant step have been well studied with regards to COD performance. Higher propulsive force and lower braking force during the plant step have been shown to result in faster COD performance (Jones et al., 2017; Spiteri et al., 2013; Spiteri et al., 2015a). It was hypothesised in this study that faster COD performance would have higher propulsive impulse at the plant step. However, the results from this study showed no significant difference in propulsive impulse between faster and slower COD performers during DL and NDL COD as well as pooled DL and NDL COD. On the contrary, significantly lower mean propulsive impulse and high mean braking impulse were observed at the plant step in the pooled DL COD performance (Table 7, Figure 4). However, this finding is similar to that reported by Dos'Santos et al. (2016) who also found lower propulsive force at the plant step during faster COD performance. Similarity in findings could be explained by the different COD background and techniques of the participants from various sports in Dos'Santos et al. (2016) and the current study, compared to studies with participants all from a single sport (Jones et al., 2017; Spiteri et al., 2015a) with similar COD techniques.

Technique such as a low forward leaning body position with minimal movement of the hip and trunk (Marshall et al., 2014; Sasaki et al., 2011), and kinematic factors such as higher stride frequency (Hewit et al., 2013) have been shown to be associated with faster COD performance. It is possible through better technique, more efficient use of propulsive force can result in faster acceleration and subsequently faster COD performance. Marshall et al. (2014) reported that faster 75^{o} COD was significantly ($p \leq 0.01$) associated with a greater rate of force development of the ankle (r = -0.77), torso rotation (r = -0.51) and smaller lateral hip movement during the plant step of the COD (r = 0.54). Faster COD performers in this study could have had greater torso rotation resulting in an earlier alignment of COM to the intended direction and subsequently applied a greater portion of propulsive impulse for accelerating at the intended direction at the plant step. Therefore, faster COD performance can be achieved with less propulsive impulse due to better body alignment. As kinematic and joint kinetic analyses were outside the scope of this study, this explanation was not investigated and is speculative. Further studies are required to examine the technique and joint kinetics of 90^{o} sidestep COD performance.

4.3 Muscle function difference between faster and slower COD groups

It has recently been shown that faster COD performance result from faster deceleration and greater eccentric strength (Jones et al., 2017; Spiteri et al., 2015a). Thus, it was hypothesised in this study that participants with faster COD performance would have greater maximal eccentric strength than slower counterparts, but the current study did not find any significant difference in eccentric strength between faster and slower COD performers (Tables 9, 12 and 15). Furthermore, the faster COD performers were not necessarily eccentrically stronger relative to their concentric or isometric strength (Tables 10, 11, 13 and 14). The results indicate that eccentric strength may not the differentiating factor for faster COD. The faster COD performers could distribute braking load among the last three braking steps to reduce the eccentric strength demands during each braking step. Therefore, faster COD performers may have had better estimation of the load they can could tolerate and managed their braking to within their strength capacity. Faster COD from better management of strength capacity was also observed by Hori et al. (2008). They found no significant difference in 180^{o} COD time between stronger and weaker athletes based on 1RM hang power clean assessment and explained that COD ability could be dependent on the athlete's ability to regulate their deceleration and acceleration based on their strength capacity in addition to maximal strength capacity. Braking load management prior to the COD plant step could be unique to each individual and no single strategy was significant among the participants of this study.

The ability to transfer the body's COM during the COD plant step has been reported to be a differentiating factor between faster and slower COD performance (Hewit et al., 2013; Sasaki et al., 2011; Spiteri et al., 2013). Isometric strength of the lower limb is required for the transfer of COM during the plant step of COD (Nimphius, 2014) and faster athletes demonstrate significantly greater isometric strength (Spiteri et al., 2013; Spiteri et al., 2015a) indicating the importance of isometric strength for faster COD performance. Spiteri et al. (2015a) discussed that greater isometric strength enabled athletes to stay in a lower position during the transition of COM to maximise acceleration by triple extension of body during the propulsive phase of the COD which resulted in higher propulsive impulse of faster athletes. Findings from the current study supports this, as faster participants during NDL COD demonstrated significantly greater isometric strength of the knee extensors and flexors as well as isokinetic 90$^{o}\cdot s^{-1}$

concentric strength (Table 12), which are required for acceleration in the new direction (Nimphius, 2014). However, no difference in propulsive impulse was observed between faster and slower NDL COD participants and faster NDL participants had lower propulsive impulse than slower NDL participants (Table 6). Greater isometric strength of the knee extensors and flexors, and greater concentric strength of the knee extensors but lower propulsive impulse of faster participant in the study suggest that they had better movement mechanics than slower participants as greater strength did not result in higher GRF. This result supports the earlier explanation that faster COD can be achieved from better translation of the body and more efficient use of propulsive impulse through better COD technique. As joint kinematics and kinetics were not measured, it is unclear how different strength capacity would influence body position and technique. Therefore, further study is required investigating the strength, and joint kinematics and kinetics to better understand what movements result faster COD performance.

4.4 Relationships between ground reaction force and muscle function parameters

This study also investigated the relationships between the GRF during COD performance and muscle function variables. It was initially hypothesised that, braking impulse at the PEN and PEN-1 steps, maximal and isokinetic eccentric strength, and drop jump RSI would be significantly associated with COD performance. However, no significant associations between GRF variables and DL and NDL COD performance were found (Figures 6 and 7) and none of DL muscle function variables were significantly associated with DL COD performance (Figures 8, 9, 10, 11 and 12). A few significant associations were observed between NDL muscle variables and NDL COD performance as shown Figure 18. This is in line with the cross-sectional analyse of this study between faster and slower COD performance which suggest that faster COD may be due to better technique rather than the participant's GRF during deceleration and muscle function. The difference in GRF correlation findings with previous studies

(Dos'Santos et al., 2016; Jones et al., 2017) may be due to the COD angle which is commonly an 180° COD, therefore requiring different braking loads compared to the 90° COD in this study and the use of COD total time as the performance measure. An 180° COD requires a different braking load compared to the 90° COD used in this study. In comparison to 180° COD, Jones et al. (2016a) reported that peak braking force at the PEN step during a 90° COD was 40% lower than that at the PEN step during 180° COD. Rather than focusing braking at the PEN step during 180° COD, the reduced braking load for 90° COD may result in different braking strategies for faster COD. Additionally, it is possible the role of eccentric strength is dependent on the magnitude of approach velocity (Jones et al., 2017) which is reflected in COD total time but not 1-1m COD time used in this study, therefore, no association between COD performance and eccentric strength was observed.

It is possible that faster DL COD participants had better knowledge of the braking load that their muscles could tolerate and selected a strategy that allowed them to achieve a faster COD (Hori et al., 2008; Jones et al., 2017; Spiteri et al., 2014). However, during NDL COD, participants may be less proficient at planning their deceleration and estimating tolerable load at the plant step. Therefore, stronger participants were faster during NDL COD as they were able to adapt to the sudden and large braking load from poor estimation of their deceleration and still able to adopt an effective body position for reacceleration at the plant step.

Correlation results of NDL COD and NDL muscle functions are consistent with previous research demonstrating the relationship between knee extensors and flexors eccentric strength for COD performance (Jones et al., 2009; Jones et al., 2017). Jones et al. (2017) found significant ($p \leq 0.05$) correlation between the 505 COD test and bodymass normalised eccentric isokinetic torque of the knee extensors (r = 0.674) and flexors (r = 0.603) in elite female soccer players. Similarly, Jones et al. (2009) reported moderate significant ($p \leq 0.05$) correlations in bodymass normalised eccentric isokinetic torque knee extensor (r = 0.506) and knee flexor (r = 0.592) torque in university team sport athletes. The current study also showed significant correlations between NDL 1-1 m COD time and eccentric isokinetic torque of the knee flexors (r = 0.648, p = 0.048) and the knee extensors (r = -0.470, p = 0.05). The function of eccentric knee flexor strength may be to control the forward inclination of the trunk and hip during the plant step (Sasaki et al., 2011) and to prevent over rotation of the COM (Jindrich et al., 2006), while isometric strength stabilises the hip and knee joint during push off the plant step (Besier et al., 2003; Marshall et al., 2014).

Reactive strength is an important quality for COD as the COD plant step place a high demand on the stretch shortening cycle of the lower limb (Young et al., 2002; Young et al., 2015b). The current study result supports this as demonstrated by the large significant correlation (r = - 0.556, p = 0.048) between 60 cm drop jump RSI and COD performance. In addition, given the plant propulsive contact time of faster and slower NDL COD in this study was 0.21 s ± 0.03 s and 0.22 s ± 0.04 s respectively. It appears that faster NDL COD participants with better fast stretch-shortening cycle ability (amortisation time < 0.250 s), were able to tolerate a larger eccentric load and utilise stored energy from the rapid eccentric loading to produce propulsive force in a short time resulting in faster accelerating at the plant step. Previous studies on the relationship between drop jump RSI and COD performance have shown mixed results, ranging from non-significant low to moderate correlations (r = -0.140 – -0.401) (Barnes et al., 2007; Foden et al., 2015; Jones et al., 2009) to large significant correlations (r = -0.440 -0.645) (Delaney et al., 2015; Young et al., 2002; Young et al., 2015b). Drop jump height may explain the inconsistency in the studies that observed no relation to COD performance. A 30-cm drop jump height used by the aforementioned studies (Barnes et al., 2007; Foden et al., 2015; Jones et al., 2009) may be ineffective in eliciting the large eccentric load required during the COD plant step. This is supported by the lack of significant correlations of 20 cm and 40 cm drop jump RSI found in the current study. As the load on the body during deceleration can be up to three times body mass (Spiteri et al., 2015b), using a higher drop jump height may be more specific to the task of deceleration during COD.

It should be noted that of all the isokinetic measurement taken, only NDL $90^{o}\cdot s^{-1}$ eccentric and isometric torque correlated significantly with COD performance. This supports earlier explanations that other factors such as COD technique is likely to contribute more to COD performance in recreational level athletes. Faster COD in higher level athletes have significantly greater eccentric strength and were able to transfer eccentric strength to greater braking GRF (Jones et al., 2017; Spiteri et al., 2015a) but this was not case in the current study. Further kinematic, kinetic and strength examinations of COD deceleration in this population should be conducted comparing different COD angles is required.

4.5 Limitation of the study

Limitations of the present study was the population of participants from various sports background. Although every sport required the use of a 90^{o} COD, the technique to execute the COD as well as familiarity of this type of COD could have varied among their sport, therefore contributing to the lack of significant findings. In particular, tennis and squash athletes, given the court dimensions of their sport will not perform a COD from a long run-up frequently. Tennis athletes may only perform this type of COD when employing a serve and volley strategy while squash athletes may only perform this type of COD to retrieve drop shots from the opponent. The analysis of just three steps of a COD task, does not necessarily represent deceleration for all the participants as some participants took up to five steps which could also be due to the COD techniques of their respective sports. As COD tasks are angle and technique dependent (Besier et al., 2001b; Havens et al., 2015; Jones et al., 2016a; Suzuki et al., 2014), the braking strategies discussed in this study are only applicable to a 90^{o} side-step cut COD task. Additionally, the findings discussed in this study are only applicable to pre-planned COD and introduction of reactive component will result in different kinetics, kinematic and neuromuscular characteristics (Besier et al., 2001a; Spiteri et al., 2015b; Young et al., 2015b). Lastly, muscle function measurements taken were mostly of the knee, as it was initially expected that the largest effort during deceleration will occur at the knee muscles. However, the lack to significant findings here illustrates various strategies to overcome deficit in the strengths required during deceleration while still achieving faster COD performance. Therefore, further research is required to investigate the kinetic, kinematic and strength determinants of COD performance as well as deceleration.

4.6 Conclusion

In conclusion, the present study showed that several steps are required for COD deceleration before COD plant step. A minimum of two steps prior to the plant step should be recorded and analysed when examining COD deceleration, due to the fact that early deceleration within these two steps play a role in COD performance. The current study shows that there are different deceleration strategies and mechanics for faster COD and they are also different between DL and NDL. It is likely that difference in COD between DL and NDL is due to unequal COD proficiency on both legs in recreational athletes. Therefore, COD training on the NDL in recreational athletes should be emphasised over improvements in lower leg muscle function. With regards to deceleration drills for training COD in recreational level athletes, instructing athletes to reduce their braking distance may be a beneficial in improving their deceleration ability as it will gradually increase braking demands on each leg. Instructions to reduce deceleration distance have also been shown to be more beneficial to COD performance as compared to traditional speed and agility training program (Lockie et al., 2014a). Plyometric training for deceleration should be performed with to higher eccentric loading such as weighted countermovement jump or drop jump, to enhance the ability to utilise stored energy during deceleration to reaccelerate after the plant step. Deceleration and plyometric should be included in athlete’s COD training.

4.7 Future studies

Future studies should examine the combined joint kinetics and multifactorial strategies of COD deceleration of COD performance rather than individual steps. In addition, athletes from the same sport should be used to examine braking strategies of individual athletes without the confounding factor of different sporting background and experience if possible. Comparison of different braking demanding COD angles (60^{o}-180^{o}) (Dos’Santos et al., 2018) is also required to further confirm PEN-1 braking. Further research is required to investigate the role of PEN-1 in different COD angles and in different populations.

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Appendices

Appendix A Information letter

Edith Cowan University
School of Medical & Health Sciences

Information Letter for Participants

Deceleration kinetics before Change of Direction

Thank you very much for your interest! Please read this information letter carefully before you decide to participate. If you decide not to participate, there will be no disadvantage to you of any kind and we thank you for considering participating. If you have any questions, please do not hesitate to ask me anytime.

Researchers and contact details

This research project is being undertaken as part of the requirements of a Master candidature (Sport and Exercise Sciences) at Edith Cowan University (ECU). The responsible researcher for this project are:

Master candidate: Walter Yu (y.walter@ecu.edu.au) 6304 3780
Supervisor: Prof. Ken Nosaka (k.nosaka@ecu.edu.au) 6304 5655
Co-supervisor: A/Prof. Sophia Nimphius (s.nimphius@ecu.edu.au) 6304 5848

Further details of supervisors and the School of Medical and Health Sciences are available at http://www.ecu.edu.aus-1chools/medical-and-health-sciences/our-staff

Background

Deceleration is often required before a change of direction, with greater deceleration required as the change of direction (COD) increases in angle or entry velocity. Higher braking impulse especially at the penultimate step was found to result in higher propulsive impulse during the final step of COD leading to faster acceleration and decreased overall time in a COD task. Therefore, better braking capacity may be an important quality for better COD performance. However, previous studies examined the last two steps of deceleration prior to a COD only. It is possible that deceleration begins earlier than the last two steps, therefore the braking at the penultimate step may not necessarily represent the whole deceleration prior to COD. The process of deceleration requires eccentric contractions, therefore it is important to assess eccentric muscle strength in relation to the deceleration ability. Previous studies have examined eccentric muscle strength using an isokinetic dynamometer or an eccentric squat protocol, however eccentric strength have yet to be evaluated using an eccentric ergometer. This measure may provide a better insight into the requirement of eccentric capability during deceleration due to the repeated multi-joint coordinated effort required.

Purpose of this research project

This research aims to examine the deceleration prior to and during the COD from the onset of deceleration to determine the mechanical characteristics of deceleration in faster COD performance when compared with slower COD performance; and to investigate the association between several different muscle function tests and COD performance.

Study 1 methodology

You will be asked to come to the biomechanics laboratory (JO22.116) for 2 sessions as part of study 1. The first session is a familiarisation session, and the second and third session are data collection sessions. In all sessions, there will be a 10 minute warm-up and practice of the COD task. As you will be wearing a Lycra suit during testing, you are advised to avoid wearing baggy sports clothing to ensure the proper fitting of the suit.

Familiarisation Session: You will perform the 10-minute dynamic warm-up which includes a straight sprint at 50%, 75% and 100% effort. After the warm-up, you will be required to perform the COD task using your preferred leg to perform the COD. The preferred leg will be recorded and must be used when performing a COD to the preferred side, whereas the other leg must be used when performing COD to the non-preferred side.

Data collection session: After the warm-up exercise as per familiarisation session, you will wear the Xsens suit and practice running the COD task in the suit for 5 minutes or until you are comfortable with the suit. You will perform 3 trials on the preferred side and 3 trials on the on preferred side in this order. For the trial to be valid, you must attain at least 4m·s-1 during the linear sprint and run within the designated path to ensure a 90º cut is performed and deceleration steps are recorded on the force plate. You will be given 2 minutes rest after each. Your running and COD will be recorded on a camera to allow visual confirmation of the COD task and to calculate the step rate during deceleration.

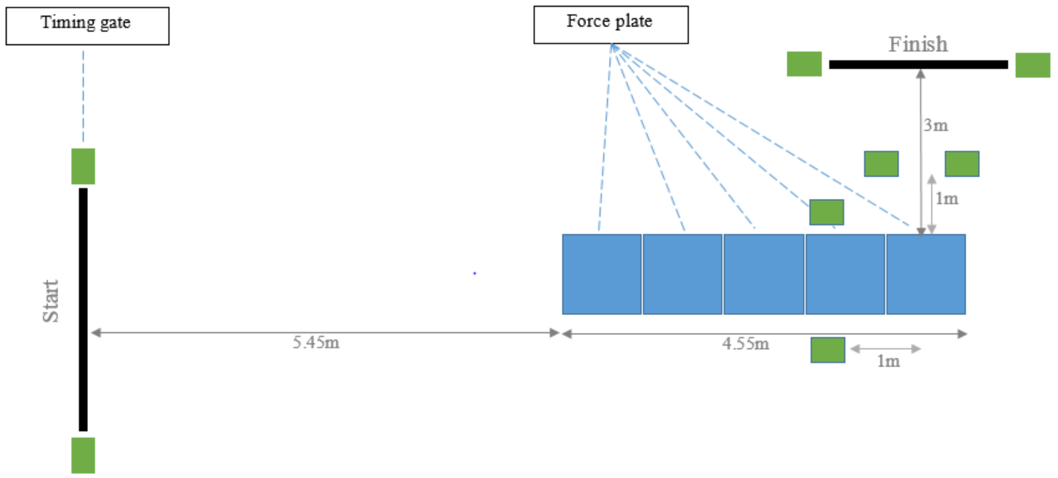

Figure 1. Layout of the COD task and placement of equipment

Study 2 methodology

Familiarisation session: You will be asked to go to different locations for each muscle function test which will be introduced to you during familiarisation. During familiarisation session, you will perform all the muscle function test. This will take approximately 3 hrs 30 mins. The familiarisation will be carried out in the order listed: drop jump, eccentric ergometer, leg press, leg curl and isokinetic dynamometer. During familiarisation, you will only reach 80% of your perceived maximal effort during leg press and curl. During drop jump, isokinetic dynamometer and eccentric ergometer test you will go through the same protocol as data collection.

Drop jump: You will perform a drop jump from a 40-cm box onto a force plate. You will hold a carbon fibre pole across your shoulders to limit arm movement. For the drop jump to be valid, you must step off the box (not jump off) with the preferred leg and perform the jump on the force plate. You will be instructed to “jump as high as possible and as fast as possible”. You will be given 2-minute rest between trials and the highest trial will be used for data collection.

Drop Jump

Unilateral concentric and eccentric leg press 1RM: You will be asked to go to the Vario clinic (19.133) for this test. You will perform the concentric leg press on your preferred leg first. You will warm up at 5-10 repetitions at 40-60% of your perceived maximum then 3-5 repetitions at 60-80% of your perceived maximum. After the warm-up, you will proceed to 1RM test. The load will be lowered from the top position using a winch and partially supported by you. At 90 knee angle, you will hold the weight for 1 sec before pushing as hard as you can. You will have a 3-minute rest between sets. Weight will be increased in small amounts (2.5kg to 5kg) or according to your perceived ability. The load will be increased until you fail to perform the leg press. 5 attempts will be given before declaring failure. Eccentric 1RM will start from the 100% of your concentric 1RM and protocol will be the same as the concentric 1RM.

Unilateral concentric and eccentric leg curl 1RM: The leg curl protocol will be the same the leg press. The progression of weight will be the same as the leg press protocol as well. For eccentric protocol, you will start from the end of the range of motion during concentric 1RM.

Isokinetic torque assessment: Maximal voluntary contraction (MVC) torque of the knee extensors and flexors will be assessed concentrically and eccentrically on an isokinetic dynamometer. You will perform knee extension and flexion at angular velocities of 60°s-1, and 240°s-1 for concentric contractions and eccentric contractions. The range of motion of the knee joint will be set to 0 to 110° whereby the 0° is full leg extension. Lateral movement of the knee will be restricted with a thigh strap and ankle strap to stabilise the leg. You will start your preferred leg to push-off during the side-step COD test. Two warm up sets of knee extensor and knee flexor at 50% and 80% of your perceived maximum effort will be performed before the maximal contraction trials. You will start with maximal concentric contractions at 60°s-1 of the knee extensor followed by the knee flexor alternatively. A 2-minute rest will be given after both concentric contractions before performing the second set. You will perform 5 trials of each contraction and the trial with the highest torque value will be used for data analysis. All the concentric contractions at all three angular velocities will be completed before maximal eccentric contractions on the same side. Eccentric assessment will start with the knee flexor followed by the knee extensors in succession. A 5-minute rest will be given between each angular velocities. After you have completed all sets on the

same side, you will rest for while the investigator switches the set-up for the other leg. The protocol will the same for each leg.

Isokinetic dynamometer

Eligibility

Men aged 18 to 30 of age who have been participating in invasion (AFL, soccer, rugby etc) or court sports (i.e. tennis, badminton, basketball, etc) for at least 2 years. You must have at least 2 formal training sessions a week during off-season and 1 training and 1 competition session a week during the season. For you to be eligible for the study you must not have any musculoskeletal injuries in the lower limbs.

Measurements and Variables

1) Physical characteristics: Your age, height, body mass will be recorded before data collection

2) COD kinetics: Your braking force, contact time and impulse of each step from the onset of deceleration as well as propulsive force at the plant step will be recorded on the force plates

3) COD performance: your 1m to 1m COD, total time and exit velocity will be recorded using timing gates and speed guns.

4) Muscle function: Your strength will be assessed using drop jump, leg press, leg curl, and eccentric cycling and isokinetic dynamometer.

Potential risk of study participant

You may experience muscle soreness after the COD session. Eccentric exercises may produce muscle damage and cause soreness and swelling in your thigh muscle. Although this effect can be mitigated with proper familiarisation. Should you experience muscle strain as a result of testing, the primary investigator is on site and will immediately treat the injury according to first-aid protocol. During exercise, you will be monitored closely, should you feel unusual levels of fatigue or there is an occurrence of breathlessness, nausea or slight fainting the exercise will be stopped immediately. In the event of an emergency or severe injury, management protocol will be followed and First Aid will be applied by the primary investigator. A defibrillator device is available in the exercise physiology laboratory. Afterwards you will be referred to a medical doctor.

Benefits of study participation

You will learn about your COD performance and understand your force profile during the COD. You might improve your COD performance after the study by improving force application during different phases of COD. The information gained as a result of participation will also provide valuable insight into your current COD performance and physical capacity. You will also experience a different and interesting form of exercise that has been shown to increase lower limb strength. Lastly, on completion of this study, a $40 Coles Voucher will be made available to compensate for your time and travelling/parking costs.

Confidentiality of information

All the information that you provide and collected during the testing sessions will be available only to the listed investigators. Access to the raw data will be limited to the listed investigators. All personal data will be encrypted and kept securely in a password protected hard disk. Consent forms and hard copies will be kept in a locked drawer in the researcher's office.

Results of the research study

The results of this study will be part of my Master's thesis and will be subjected to publication in academic peer-reviewed journals and presented in conferences or seminars in the future. All the published work will not include any information that may identify any participants. A copy of your results can be obtained from the primary investigator.

Participation rights

Your participation in this study is entirely voluntary. You have the right to withdraw from study or refuse any session any time without any reason and free of consequences. Upon request of withdrawing from the study, you will offered a copy of your data before it is destroyed. You have the right to receive information regarding your own data and results at any time during the study from the primary investigator. Signing the informed consent form does not remove your rights to withdraw from this study.

Medical Questionnaire

This study involves a testing protocol, it is required that you be healthy at the time of testing. For this reason you will be asked to complete a medical questionnaire prior to the commencement of testing. Answering 'Yes' to a question will not always disqualify you from participation in the study. However you may be asked to consult your doctor for clearance prior to participation.

Questions / Further Information

This project has been approved by the ECU Human Research Ethics Committee. It is intended to present the results of this research through conferences and publish journals and reports. Published results will not contain information that can be used to identify participants unless specific consent for this has been obtained.

If you have read and understood the description of this study and wish to volunteer as a subject, the next step is to sign the informed consent form. By signing this form you acknowledge that you are aware of the procedures, tests and risks involved.

Should you have any questions relating to any of the information provided above, please feel free to contact me for a further explanation. If you have any concerns about this research, or would like to speak to an independent person, you may contact:

Research Ethics Officer
Human Research Ethics Committee,
Edith Cowan University
270 Joondalup Drive, Joondalup WA 6027
Phone: (08) 6304 2170
Email: research.ethics@ecu.edu.au

Thank you for taking time to read this information letter. If you have any questions or require any further information about this project, please contact Walter Yu (y.walter@ecu.edu.au).

Primary Investigator: Walter Yu, BSc (Sport Science), Master Candidate
School of Exercise and Health Sciences,
Edith Cowan University
270 Joondalup Drive, Joondalup WA 6027
E-mail: y.walter@ecu.edu.au
Office: Building 21.501
Phone (ECU): 6304 3780

Appendix B Informed consent

Edith Cowan University
School of Medical & Health Sciences

CONSENT TO PARTICIPATE IN RESEARCH

Deceleration Kinetics before Change of Direction

I, ____ hereby agree to volunteer in a scientific investigation performed at Edith Cowan University.

The investigation, and my part in the investigation, have been outlined and explained to me in detail and I understand the explanation. I received a copy of the procedures, and a description of any risks and discomforts has been provided to me and discussed in detail with me.

I, as a volunteer in this study,

- Have read and understood the information sheet about this research project and the testing protocols have been explained to me.
- Have been given an opportunity to ask any questions and all such questions and inquiries have been answered to my satisfaction.
- Understand that I am free to ask any questions and that they will be answered to my satisfaction at any time.
- Understand that as part of the testing I will be required to
    - Wear a Lycra suit with inertial sensors underneath the suit.
    - Sprint maximally and perform a change of direction under high load
    - Maximal voluntary contractions (i.e. 1RM strength & isokinetic test)
    - Jump height measurements
- Understand that the maximal and isokinetic strength, jump height, and eccentric cycling exercises may lead to muscle soreness and discomfort if I am unaccustomed to the technique and exercise type.
- Understand that I am free to withdraw my consent and to discontinue participation in the project or activity at any time and without any reason or explanation required from me.

- Understand that my data will remain confidential with regard to my identity.
- Certify that, to the best of my knowledge and belief, I have no physical condition that would increase the risk to me of participating in this investigation.
- Agree that the research data obtained from this study may be published, provided I am not identifiable in any way.

Participant ________________________________

Date ______________________

I, the primary investigator, was present when the study was explained to the participant in detail to the best of my knowledge and belief it was understood. The detail includes the following: the nature, the purpose and the risk/benefits of the research. Lastly, the participant have provided consent freely.

Investigator ________________________________

Date ______________________

Walter Yu, BSc (Sports Science), Masters Candidate
Primary Investigator | Deceleration Kinetics before Change of Direction
School of Medical and Health Sciences
Centre for Exercise and Sports Science Research
Edith Cowan University
270 Joondalup Drive, Joondalup WA 6027
Mobile phone:
Email: y.walter@ecu.edu.au

Associate Investigators:
Professor Ken Nosaka, PhD, Principal Supervisor
Associate Professor Sophia Nimphius, PhD, Co-Principal Supervisor
Associate Professor Greg Haff, PhD, Associate Supervisor

Appendix C Medical Questionnaire

Edith Cowan University
School of Medical & Health Sciences

Participant / Health Screening Questionnaire

To assist us with this check-up please complete this health-screening questionnaire. Read the questions carefully and answer each one honestly: Tick either yes or no.

		Yes	No
1.	Are you between the ages of 18 and 30 years? Please specify age: ________________	☐	☐
2.	Are you currently suffering from any illness? If so provide details, (type and severity) ____	☐	☐
3.	Has your doctor ever said you have a heart condition? If so provide details: ____	☐	☐
4.	Do you have any history of epilepsy?	☐	☐
5.	Do you have any history of severe migraines?	☐	☐
6.	Is your doctor currently prescribing drugs for any medical condition? If so please comment, (supplement and dosage): ____	☐	☐
7.	Do you have any known neurological disorders that would make exercise problematic, or where exercise may aggravate the condition? If so provide details: ____	☐	☐
8.	Do you have any known neuromuscular disorders that would make exercise problematic, or where exercise may aggravate the condition? If so provide details: ____	☐	☐
9.	Have you been diagnosed with any attentional disorders? If so provide details: ____	☐	☐
10.	Are you currently taking any other medication? If so please comment: ____	☐	☐
11.	Have you had any lower body injury in the last 6 months?	☐	☐
12.	Have you ever had a serious asthma attack during exercise? If so, do you require medication?	☐	☐

13.	Do you, or could you reasonably, have an infectious disease that might be aggravated by exercise? If so, please provide details: ____	☐	☐
15.	Do you currently have an injury that might, or be affected by, exercise? If so provide details: ____	☐	☐
16.	Do you consume tea and or coffee? If yes, how many cups a day? ____________________________________	☐	☐
17.	Do you know of any other reason why you shouldn't participate in this study? ____	☐	☐
18.	Is there any other condition not previously mentioned which may affect your exercise performance?	☐	☐

I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction.

Participant's Name   Investigator's Signature

__________________________________   ________________________

Signature________________________   Date: __________________

Date…………………………..

People to Contact in Case of Emergency

This form will be kept in confidential file and used only in case of an emergency. In the event of an emergency (accidental or serious injury), please immediately inform the following:

1. Name: ____________________

   Telephone: ____________________

   Relationship: ____________________

2. Name: ____________________

   Telephone: ____________________

   Relationship: ____________________

Appendix D Final checklist for participants

Edith Cowan University
School of Medical & Health Sciences

Final Checklist for Participant

Please circle one

1. **Are you aware that if you feel uncomfortable with any testing procedure you should tell the researcher immediately, and that YOU CAN STOP your participation at any time?** **YES** **NO**

2. Are you aware that, although very rare, maximal exercise can result in fainting, severe exhaustion or cardiac events leading to death? YES NO

3. Are you aware that the fatigue caused by the exercise can impair your ability to perform tasks such as driving for a short while after the cessation of exercise? YES NO

4. Have you been given the opportunity to view the photos outlining the change of direction technique require (sidestep cut)? YES NO

5. Have you been given the opportunity to view the photos outlining the maximal exercise testing techniques (leg press & leg curl)? YES NO

6. Are you aware that your muscles may be swollen for several days after the exercise YES NO

Name of volunteer: ____________________________

Signature of volunteer: _________________________ Date: _______________

Name of witness: ____________________________

Signature of witness: _________________________ Date: _______________

Appendix E Advertisement

Edith Cowan University
School of Medical and Health Sciences

FREE PERFORMANCE TESTING!

Participants Required for Masters Research

We need your help to find what factors contributes to change of direction (COD) performance and the muscle functions involved to decelerate during COD.

Who: Males (18-30 yrs) participating in sports that has frequent COD (e.g. soccer, AFL, rugby, basketball, etc.) or racket sports (tennis, squash, etc.). Must have 2 years' experience and 2 sessions a week.

Time commitment: six sessions – 0.5 hrs to 3.5 hrs

Where:

- Session 1 – 3: Biomechanics Lab (JO 22.116)
- Session 4 – 6: Physiology Research Lab (JO 19.139)

When: Book a time now!

What is required:

- Participation in a COD test
- Participation in 5 physical function tests

If you or someone you may know are interested in participating in this research or have any questions, please contact:

Walter Yu
Ph: 0432149482
Email: y.walter@ecu.edu.au

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y.walter@ecu.edu.au

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Appendix F Ethical Clearance

From: Research Ethics
To: Yu WALTER; [redacted]
Cc: Ken NOSAKA; Sophia NIMPHIUS; Greg HAFF; Research Assessments; Joseph SIM
Subject: Project 17254 YU Ethics Approval
Date: Thursday, 8 June 2017 4:25:59 PM
Attachments: Conditions of approval.pdf

Dear Walter

Project Number: 17254 YU
Project Name: Deceleration Biomechanics before Change of Direction
Student Number: [redacted]

The ECU Human Research Ethics Committee (HREC) has reviewed your application and has granted ethics approval for your research project. In granting approval, the HREC has determined that the research project meets the requirements of the N*ational Statement on Ethical Conduct in Human Research*.

The approval period is from **8 June 2017** to **28 February 2018**.

The Research Assessments Team has been informed and they will issue formal confirmation of candidature (providing research proposal has been approved). Please note that the submission and approval of your research proposal is a separate process to obtaining ethics approval and that no recruitment of participants and/or data collection can commence until formal notification of both ethics approval and approval of your research proposal has been received.

All research projects are approved subject to general conditions of approval. Please see the attached document for details of these conditions, which include monitoring requirements, changes to the project and extension of ethics approval.
Please feel free to contact me if you require any further information.

Kind Regards

Faye

Faye Walmsley
Ethics Support Officer
Office of Research & Innovation, Edith Cowan University,
270 Joondalup Drive, Joondalup, WA 6027
Tel: +61 08 6304 5032 | Fax: +61 08 6304 5044 | CRICOS IPC 00279B
Email: research.ethics@ecu.edu.au

Appendix G is not included in this version of the thesis

The poster featured in Appendix G is available at https://ro.ecu.edu.au/ecuposters/27

Yu, W., Nimphius, S., Haff, G. G. & Nosaka, K. (2018). Braking ground reaction force during 90^0 sidestep cut and leg muscle strength. *Poster presented at the 11th International Conference on Strength Training 2018, held Perth, Western Australia, 30 November – 3 December, 2018.*

Appendix H is not included in this version of the thesis